THE HCHC-XX FAMILY OF HIGH-CURRENT COMPACT CYCLOTRONS: DESIGN, SIMULATION, TESTS

D. Winklehner[1]
[1]Massachusetts Institute of Technology, Cambridge, MA, USA
On behalf of the IsoDAR Collaboration

Abstract

The High-Current H_2^+ Cyclotrons (HCHC) were originally conceived for the IsoDAR experiment, which would place an intense accelerator-driven electron-antineutrino source near a high-resolution underground scintillator detector to enable precision beyond-standard-model searches (e.g., sterile neutrino oscillations). The HCHC design accelerates 5 mA of H_2^+ in a compact cyclotron, exploiting vortex motion–a multiparticle collective effect that can stabilize the radial beam size–to reach proton-equivalent currents roughly an order of magnitude beyond commercial cyclotrons. The beam is efficiently bunched by a Radio-Frequency Quadrupole (RFQ) axially embedded in the cyclotron yoke, placing the RFQ exit within 25 cm of the cyclotron median plane. Upon stripping the single binding electron of the H_2^+ (during or after extraction), 10 mA of protons are delivered on target. Because the novel aspects of this design are confined to the first six turns, the concept can be readily adapted to energies from 1.5 to 80 MeV/amu (HCHC-XX, where XX denotes the energy in MeV/amu). We present the latest HCHC-XX family designs, high-fidelity IBSimu/WARP/OPAL simulations incorporating space charge and conducting boundary conditions, and the fabrication status of a 1.5 MeV/amu prototype.

INTRODUCTION

The High-Current H_2^+ Cyclotrons (HCHC)-XX was originally conceived to drive IsoDAR (Isotope Decay-At-Rest), a decisive search for sterile neutrinos and other beyond-Standard-Model physics [1–4]. The confined underground environment of this experiment necessitates a compact solution while statistics requirements call for a high beam current.

Compact high-current cyclotrons sit at the intersection of fundamental research, medical isotope production, and accelerator-driven applications, and the field has matured rapidly over the past decade. The current benchmark is PSI's separated-sector Injector 2, which routinely delivers 2.2–2.4 mA of 72 MeV protons by exploiting space-charge-dominated "vortex" operation [5] and feeds a 590 MeV Ring cyclotron at world-record beam powers above 1.3 MW with relative losses at the 10^{-4} level [6]. Among compact machines, IBA's Cyclone 70 family–installed at ARRONAX, Zevacor, Moscow, and Arizona–delivers up to 750 µA of 30–70 MeV protons with deuteron and α capability through dual extraction ports [7], while the upgraded Cyclone 30HC reaches ~100 kW of beam power for industrial isotope production [8]. Smaller AVF machines for $^{99\text{m}}$Tc and FDG production continue to proliferate, with new builds such as Indonesia's DECY-13 illustrating the global push toward in-house radiopharmaceutical drivers [9]. Against this landscape, the HCHC-XX targets a regime that exceeds today's commercial machines by roughly an order of magnitude in current (10 mA of protons after stripping) and matches or surpasses the best research cyclotrons, while remaining compact and mass-manufacturable.

APPLICATIONS OF THE HCHC-XX

In IsoDAR [1–4], paired with a ^{8}Be/^{7}Li target in a low-background underground site [10], an HCHC-60 produces three well-characterized fluxes–an intense $\bar{\nu}_e$ source, monoenergetic photons from nuclear excitations, and neutrons from spallation — enabling sensitive probes of sterile-neutrino oscillations, light "X" particles, axion-like particles, dark-sector n→n′ →n signals, and a world-leading low-Q measurement of the weak mixing angle [2, 11–13].

Beyond particle physics, the same platform serves three high-impact applied missions. In medical isotope production, an HCHC variant accelerating deuterons (an "HCDC") generates secondary neutron fluxes that open domestic, non-HEU pathways to ^{99}Mo/^{99m}Tc generators, ^{225}Ac for targeted alpha therapy, and other therapeutic radioisotopes–addressing supply-chain and regulatory bottlenecks in a growing market [15–18]. For nuclear waste transmutation, an HCHC can be the injector to a ring cyclotron driving a sub-critical reactor, converting long-lived actinides and fission products into shorter-lived species [19]. For fusion

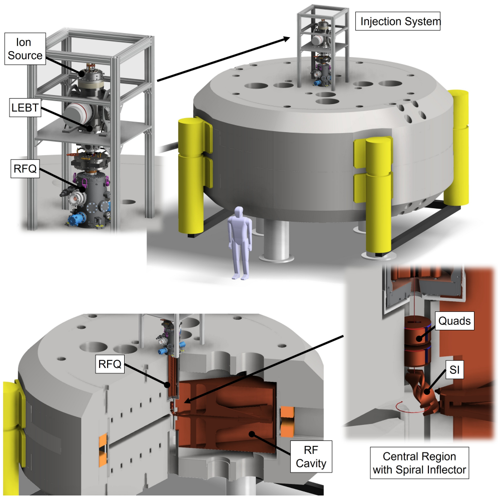

Figure 1: A CAD rendered overview of the HCHC-60 cyclotron design and its main components. We show only one of the four RF cavities for improved visibility. From [14].

materials testing, an HCDC-25 (accelerating D^+) delivering beam on a liquid Li target produces 14 MeV neutrons relevant to D-T reactor conditions; while one machine cannot match the community needs, 8 HCDCs operating in parallel at 92% uptime can–at reduced cost per unit flux [20–22].

THE HCHC-XX ACCELERATOR DESIGN

The HCHC-XX is a room-temperature, compact, isochronous (azimuthally varying field) cyclotron with four hills and four double-gap RF cavities. We recently published a Preliminary Design Report (PDR) covering all subsystems [14]; here we summarize the current status. Figure 1 shows a breakdown of the 60 MeV/amu version (HCHC-60).

The defining novelty of the HCHC-XX is that we inject the beam through an RFQ axially embedded in the cyclotron yoke, with its exit only 25 cm from the median plane. The MIST-2 produces the beam, the LEBT shapes and guides it, the RFQ bunches and modestly accelerates it, and a spiral inflector then guides it onto the median plane [23–25]. Further, we reduce space-charge effects in the LEBT and during injection by accelerating H_2^+ rather than protons, and we exploit vortex motion [26, 27].

In the cyclotron we exploit vortex motion–a stabilizing collective effect in high-current cyclotron beams: the radially outward electric self-force of the bunch combines with the external cyclotron field to "curl" the beam in the radial-longitudinal plane, producing a nearly round, stable shape that persists until extraction. We designed the cyclotron around this effect and validated it with high-fidelity particle-in-cell simulations (cf. Refs. [14, 28]) using OPAL [29]. A publication using the latest magnet and RF cavity 3D field maps is forthcoming.

We chose a split-coaxial RFQ geometry–a structure well suited to low-frequency CW operation [30, 31] — which keeps the diameter to 28 cm at the 32.8 MHz cyclotron frequency [32, 33]. It accelerates the beam from 7.5 to 35 keV/amu using about 6 kW of RF power.

The bunched beam then passes through an optimized spiral inflector with internal quadrupole moments for vertical focusing and reduced energy spread. A carefully tuned central region centers the beam, and collimators strip ~ 40 % of its halo, seeding a stable vortex. The four RF cavities accelerate the beam quickly–104 turns to 60 MeV/amu-with per-turn voltages rising from 60 kV to 230 kV. Finally, iron harmonic bars excite a resonance to generate the turn separation needed for extraction via electrostatic septum and passive magnetic channel. After extraction, the H_2^+ beam can be used directly, or stripped of its electron to deliver protons to the next stage or experiment. Stripping extraction is also a viable option, though our baseline design uses electrostatic and passive magnetic elements to preserve the H_2^+ for further use downstream.

Because the novel features sit upstream of ~ 1.5 MeV/amu, we can scale this cyclotron type to any energy from 1.5 to 80 MeV/amu.

SIMULATIONS OF THE HCHC-XX

End-to-end simulations of the HCHC-XX have been performed from the ion-source plasma meniscus through cyclotron extraction, using a chain of codes appropriate to each physical regime. The only remaining gap is the use of the exact particle distribution from the spiral inflector as input to the cyclotron simulations. Currently in the cyclotron, we are sampling from a Gaussian using the beam size and emittance from the previous step.

The MIST-2 multi-cusp ion source is modeled in 3D with IBSimu [34], which couples plasma-extraction physics to ray-tracing of the extracted ions. At 10 mA of total current and a hydrogen-species fraction of ~80% H_2^+, the simulated normalized RMS emittance at the source exit is $\varepsilon_{x,y}^{\mathrm{n,RMS}} \lesssim 0.1\,\pi\,\mathrm{mm\,mrad}$. The low-energy beam transport (LEBT) is then simulated with WARP [35] in an xy-slice configuration that includes a focusing solenoid and a fast electrostatic chopper, as well as space-charge compensation. These simulations confirm that the beam can be matched into the RFQ acceptance with $\varepsilon_{x,y}^{\mathrm{n,RMS}} = 0.175\,\pi\,\mathrm{mm\,mrad}$.

The split-coaxial RFQ was designed with RFQGen and benchmarked against TraceWin and a self-consistent WARP particle-in-cell run; consistent transmissions of ~87 % are obtained, with $\varepsilon_{x/y}^{\mathrm{n,RMS}} = 0.37/0.48\,\mathrm{mm\,mrad}$ at the RFQ exit. The subsequent spiral inflector geometry is generated by a custom Python design tool [36] and the particle dynamics, including space charge and the full electrode boundary conditions, are confirmed in high-fidelity OPAL-cycl simulations [25].

Cyclotron acceleration is simulated in OPAL-cycl using fully 3D magnetic field maps and the time-dependent RF electric fields of the four double-gap cavities, so that the radial–longitudinal coupling that drives *vortex motion* is captured self-consistently [14, 32].

For the HCHC-60 baseline we obtain an extracted beam with RMS sizes $\sigma_{x/y/z} = 2.7/3.8/4.7\,\mathrm{mm}$, normalized RMS emittances $\varepsilon_{x/y}^{\mathrm{n,RMS}} = 1.87/1.06\,\mathrm{mm\,mrad}$, and $E_{\mathrm{mean}} = 119\,\mathrm{MeV}$ with 0.12 MeV RMS energy spread, well within the requirements of the IsoDAR target station and of foreseen industrial and medical use cases. A plot of the final turns in the HCHC-60 can be seen in Fig. 2.

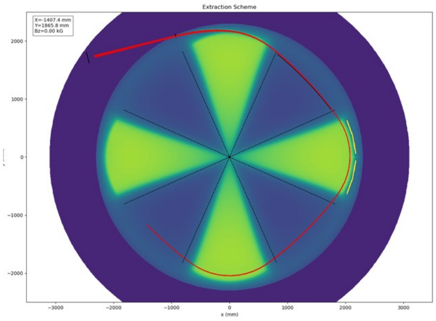

Figure 2: The final turn in the HCHC-60 cyclotron. Iron harmonic bars (right) excite a resonance. An electrostatic septum combined with passive magnetic channels guide the beam out of the machine.

EXPERIMENTAL TESTS AND MILESTONES

To demonstrate the generation and injection of a high-current H_2^+ beam into a compact cyclotron through an RFQ and the subsequent formation of a stable vortex, we designed the RFQ-DIP (RFQ - Direct Injection Project), consisting of the full HCHC injector system and a 1.5 MeV/amu test cyclotron. This project consists of three phases: Ion Source, RFQ and Cyclotron, each including the subsystems from the previous phase.

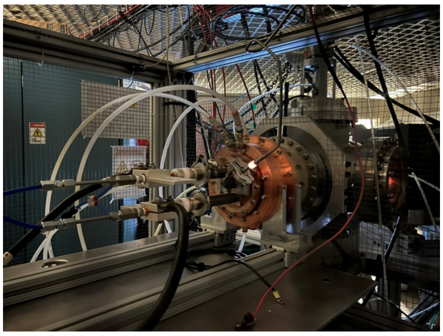

Figure 3: A photograph of the MIST-2 ion source, installed at the MIT lab.

Phase I: Ion Source We built and commissioned the MIST-2 ion source in 2024 and 2025 [37]. Figure 3 shows a photograph of the ion source. *Goals: 10 mA of total DC beam current with* $> 80\%$ H_2^+ *fraction.* $\varepsilon_{x/y}^{\mathrm{n,RMS}} < 0.1$ *π-mm-mrad.* We extracted 6 mA stably for an hour from the MIST-2. Previous measurements with the MIST-1 showed excellent agreement with simulations [38] and measured emittances as low as 0.079 π-mm-mrad. Testing the MIST-2 will resume in July 2026.

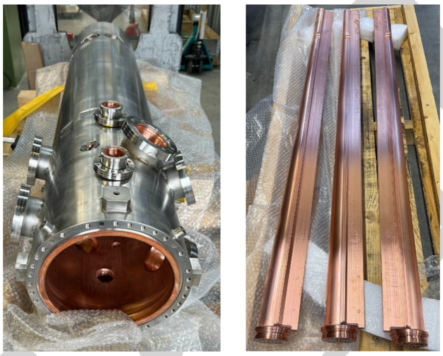

Figure 4: Left: A photograph of the RFQ tank, fully copper-plated and all flanges machined. Right: A photograph of three RFQ vanes after preliminary machining. All water channels are drilled. Courtesy of H. Höltermann (Bevatech, GmbH).

Phase II: Ion Source & RFQ The RFQ for the HCHC injection is currently under construction at Bevatech, GmbH/Kreß, GmbH. Figure 4 shows photographs from the production floor. The Factory Acceptance Tests (FATs) will be performed in June 2026 after which the RFQ will be coupled to the ion source and the commissioning (ramp-up to full power, beam tests) will commence. *Goals: Demonstrate* $> 90\%$ *transmission, measure beam timing, length, emittance, and energy spread.*

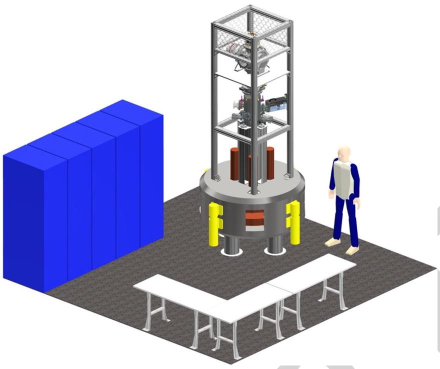

Figure 5: A CAD model of the planned RFQ-DIP test stand using the MIST-2 ion source and RFQ and injecting into a 1.5 MeV/amu cyclotron (HCHC-1.5).

Phase III: Full RFQ-DIP The HCHC-1.5 cyclotron is currently being procured, with the technical design phase initiated. A CAD rendering of the full RFQ-DIP system and its footprint is shown in Fig. 5. In parallel with the cyclotron design and fabrication, we are developing a Fast Faraday Cup mounted on a radial probe for combined radial-longitudinal beam distribution measurements.

CONCLUSION

We presented the HCHC-XX cyclotron design, high-fidelity simulations of it, and some potential applications. The HCHC-60 design is mature, and we published a PDR in 2025. Simulations of all aspects of the design have been performed and indicate that the efficiency from the ion source to the extracted beam from the cyclotron is $> 50\,\%$. Simulated losses in the extraction region are below 200 W. We built an ion source, which performs well in experiments. The RFQ fabrication will be finished within the next few months. The cyclotron technical design and fabrication will commence shortly. Beyond testing the HCHC-1.5 prototype and demonstrating RFQ injection and vortex motion, we plan to study a 25 MeV/amu deuteron version and an RL-trained agent to autonomously operate these cyclotrons in the near future.

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