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ईसीआर आयन स्रोत

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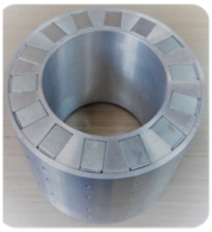

कणपुंज उत्सर्जकता को कम करने के लिए एक नया 14-ध्रुवीय बहु-शिखर

सारांश

इलेक्ट्रॉन साइक्लोट्रॉन अनुनाद आयन स्रोत (ईसीआरआईएसएस)आज के उच्च-तीव्रता वाले प्रोटॉन त्वरकों के पीछे की प्रेरक शक्ति हैं। मौलिक प्लाज़्मा भौतिकी पर प्रचालन करते हुए, ये अत्यधिक विश्वसनीय प्रणालियाँ 2.45 GHz माइक्रोवेव ऊर्जा को एक सावधानीपूर्वक गढ़े गए चुंबकीय क्षेत्र में निमज्जित हाइड्रोजन से भरे कक्ष में इंजेक्ट करती हैं। जब माइक्रोवेव आवृत्ति इलेक्ट्रॉन साइक्लोट्रॉन आवृत्ति से मेल खाती है, तो इलेक्ट्रॉन हाइड्रोजन गैस को प्रतिध्वनित करते हैं और कुशलतापूर्वक आयनित करते हैं, जिससे एक घना, स्थिर प्लाज़्मा बनता है। चूँकि वे उपभोग्य तंतुओं पर निर्भर नहीं हैं, 2.45 GHz ईसीआर स्रोत असाधारण दीर्घायु और निरंतर-तरंग प्रचालन प्रदान करते हैं, जिससे वे प्रगत नाभिकीय भौतिकी के लिए आवश्यक विशाल कणपुंज धाराओं को वितरित करने के लिए पूरी तरह से उपयुक्त हैं।

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ECR Ion Sources

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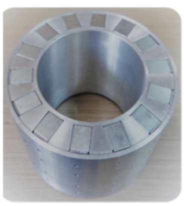

Picture of 14 pole multi-cusp

ABSTRACT

This article presents an overview of the 2.45 GHz Electron Cyclotron Resonance Ion Sources (ECRIS) developed for high-intensity proton accelerators, specifically detailing the operational three-electrode (3E-ECRIS) systems designed for LEHIPA and MEHIPA. Furthermore, it highlights advanced R&D frontiers, including a 14-pole multi-cusp geometry with a tetrode extraction system designed to minimize beam emittance, utilize permanent magnets, and enhance microwave power coupling. Finally, the paper outlines an international DAE-STFC collaboration focused on developing a tunable hexapole assembly to modulate ECR resonance and optimize plasma density distributions.

KEYWORDS: *Plasma physics, Microwave plasmas, Proton Ion Sources*

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Introduction

Electron Cyclotron Resonance Ion Sources (ECRISs) are the driving force behind today's high-intensity proton accelerators. Operating on fundamental plasma physics, these highly reliable systems inject 2.45GHz microwave energy into a hydrogen-filled chamber immersed in a carefully shaped magnetic field. When the microwave frequency matches the electron cyclotron frequency, the electrons resonate and efficiently ionize the hydrogen gas, creating a dense, stable plasma. Because they do not rely on consumable filaments, 2.45GHz ECR sources offer exceptional longevity and continuous-wave operation, making them perfectly suited to deliver the massive beam currents required for advanced nuclear physics.

The Three-Electrode ECR Ion Source

Currently, a 50keV, three-electrode ECRIS (3E-ECRIS) serves as the proton injector for the 20 MeV Low Energy High Intensity Proton Accelerator (LEHIPA) [1]. Building on this foundation, a 30keV, three-electrode ECR-IS has been developed for the 40 MeV Medium Energy High Intensity Proton Accelerator (MEHIPA) (Fig.1(a)) [2]. The system architecture and beam characterization details of the MEHIPA ECRIS are discussed below.

System Architecture: Microwaves, Magnets, and Extraction

The 3E-ECRIS system is engineered for precise plasma generation using a 2.45GHz magnetron and a WR284/340 waveguide line. To achieve ECR resonance and optimal confinement, two electromagnetic coils provide a tunable magnetic field around the nominal 875 Gauss at the chamber's central axis. Protons are then extracted through a streamlined three-electrode geometry, beginning with a 30kV plasma electrode with an 8mm aperture (Fig1(b)). The beam subsequently passes through a suppressor electrode (-2 to -5kV, 13mm aperture) to block back-streaming electrons, before exiting through a ground electrode. Finally, precise spacing; a 17mm gap between the plasma and suppressor electrodes, followed by a 2mm gap to the ground, ensures optimal beam dynamics.

Beam Characterization

To ensure the ion source meets the stringent demands of accelerators like LEHIPA and MEHIPA, the extracted beam undergoes rigorous testing using in-house developed diagnostic tools. We focus heavily on two critical metrics:

Beam Emittance

Minimizing beam emittance, a measure of the beam's phase space area, is critical to prevent beam spreading, halo formation, and downstream radio activation. Using an Allison-type scanner, the un-separated beam (H^+, H_2^+, H_3^+) emittance of the 3E-ECRIS was measured at 0.27 π·mm·mrad rms normalized for a 30keV, 15mA beam (Fig.3(a)). After isolating pure H^+ ions with a focusing solenoid, the usable beam emittance drops to 0.12 π·mm·mrad rms normalized (at 30keV, 10mA), demonstrating excellent beam quality (Fig.3 (b)) [2].

Proton Fraction

An ECR plasma generated from hydrogen gas naturally produces a mix of ions, primarily protons (H^+) alongside molecular (H_2^+ and H_3^+) ions. As LEHIPA and MEHIPA are strictly proton accelerators, the presence of heavier hydrogen isotopes reduces overall beam efficiency and contributes to space-charge degradation. The proton efficiency was characterised using a Wien filter, which applies orthogonal electric and magnetic fields to act as a precision velocity selector (Fig.4(a)). This is the destructive type of Wien filter, 1^{st} aperture of 0.4 mm to intercept the main beam, allowing only a small beamlet to pass. The species are filtered by scanning the electric field against a fixed magnetic field. Measurements taken immediately downstream of the vacuum chamber confirm a proton fraction of 60%. (Fig.4(b)) [3].

New Frontiers in ECR-IS Research

While the operational 3E-ECRIS provides a highly dependable beam, the demand for superior beam quality and system efficiency has driven the development of a novel

(a) (b)

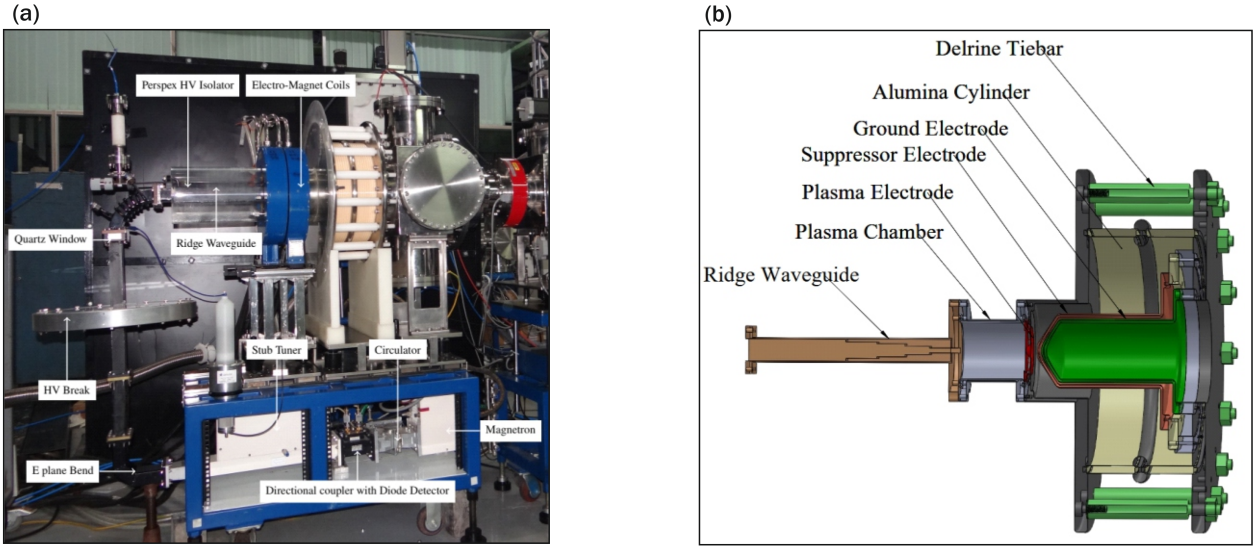

Fig.1: (a) The MEHIPA 3E-ECR ion source at VDG, (b) 3E Extraction geometry.

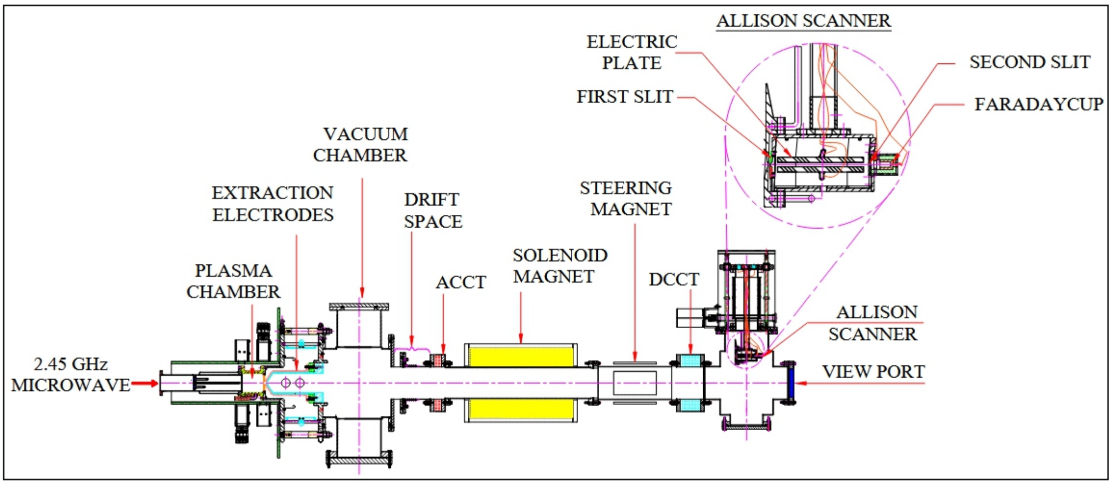

Fig.2: Experimental beam line of 3E-ECRIS.

2.45GHz multi-cusp ECR proton source to serve as a parallel injector for MEHIPA [4]. This design is driven by three core objectives:

- **Minimizing Beam Emittance:** Achieving the lowest possible emittance remains a primary goal in modern ion source design. Because axial magnetic fields in the extraction region can account for nearly 50% of total emittance [5], this new 14-pole multi-cusp geometry completely eliminates the on-axis magnetic field (Fig.5) [4, 6]. By expanding the zero-field region at the chamber's core, beam emittance becomes solely dependent on ion temperature, drastically reducing the overall emittance footprint compared to traditional axial systems.

- **Improving Microwave Power Coupling:** Another vital area of exploration is the optimization of microwave power launching schemes to maximize electron heating efficiency within the plasma chamber. By developing a novel single-step quarter-wavelength ridge coupler, the electric field amplitude can be amplified to at least five times that of conventional ridge waveguides [4]. This enhanced coupling allows for comparable plasma densities even at much lower input microwave powers, significantly boosting overall system efficiency.

- **Embracing Green Technology:** Unlike traditional systems that rely on power-intensive electromagnetic coils, this new multi-cusp geometry utilizes permanent magnets. This

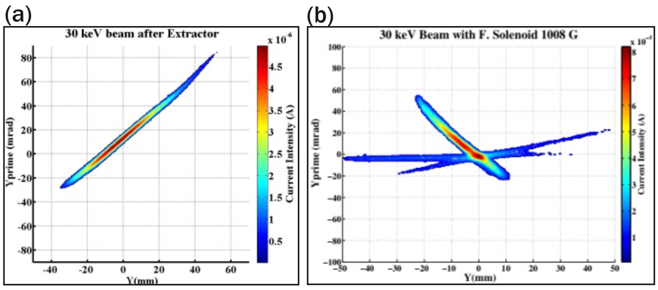

Fig.3: Beam phase space plot (a) just after the 3E-ECRIS and (b) after focusing solenoid.

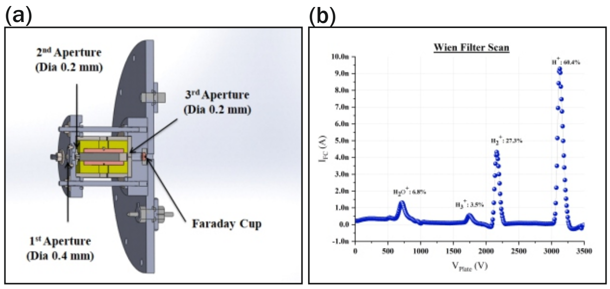

Fig.4: (a) 3D cross-section view of Wien Filter and (b) Wien filter scan spectrum.

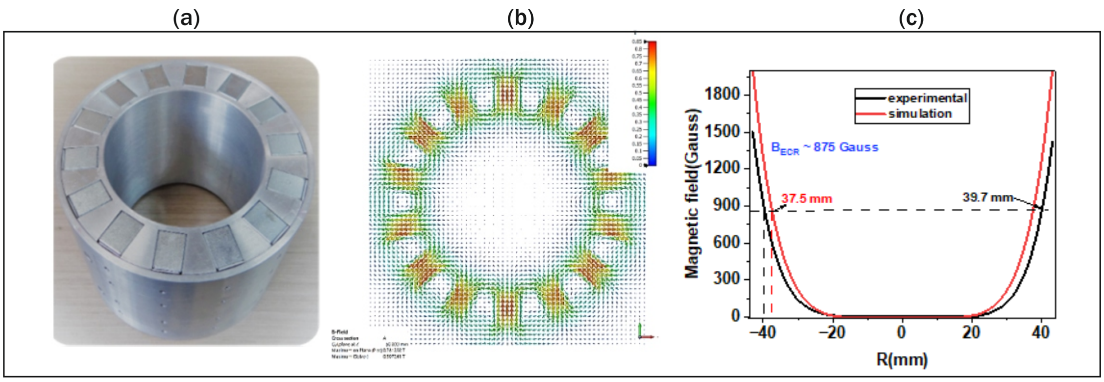

Fig.5: (a) Picture of 14 pole multi-cusp assembly and (b) its transverse magnetic field distribution using CST, (c) Radial magnetic field plot.

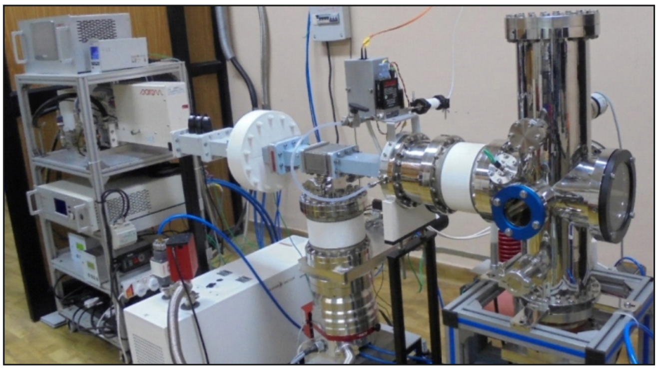

Fig.6: 14 pole Multi-cusp ECR ion source with the compact tetrode extraction system shown in inset.

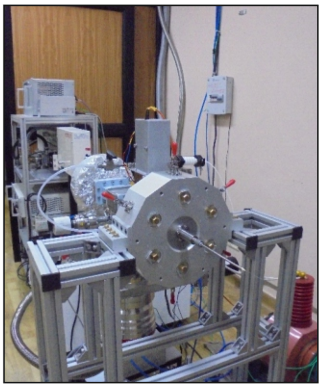

Fig.7: (a) Tunable multicusp assembly integrated with BARC test stand.

strategic shift eliminates the need for massive power supplies and cooling systems for the magnets, drastically reducing the overall energy footprint of the injector [4, 6].

To maximize beam quality and offer greater tuning capabilities, this new multicusp source employs a tetrode-based extraction design. Building on the familiar Plasma, Suppressor, and Ground electrodes, this configuration introduces an Extractor/Puller Electrode (EE) to precisely control the initial beam convergence and prevent emittance growth.

Following rigorous geometric and angular optimizations, this four-electrode assembly has been successfully fabricated (Fig.6). Preliminary beam trials have commenced, with detailed characterization of the source currently in progress(Fig.6).

International Synergy: The DAE-STFC Collaboration

The exploration of the intricate dynamics of beam formation and phase-space emittance within this novel multi-cusp geometry constitutes a key collaborative endeavour under the collaboration between DAE (BARC) and the UK's Science and Technology Facilities Council (STFC). Through this partnership, an innovative tunable hexapole multicusp assembly was conceptualized and subsequently fabricated and tested at BARC. This advanced assembly introduces several capabilities like:

- **Dynamic Tuning:** The key innovation of this assembly is the ability to modulate the ECR resonance geometry by adjusting the angular orientation of the permanent magnets.
- **Optimized Output:** By varying the rotation of the magnetic cusps, the plasma density distribution and subsequent beam current densities can be optimized.

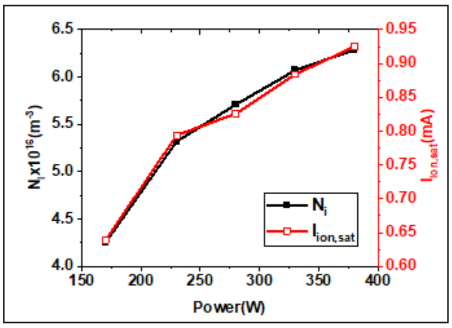

Fig.7: (b) Plasma ion density, Ni data for MW power variation, for 0° magnet orientation.

The mechanical integration of this tunable system onto the BARC test stand is now complete (Fig.7(a)). Currently, active plasma measurements are underway, utilizing optical emission spectroscopy alongside an in-house developed Langmuir probe (Fig.7(b)).

Conclusion

The operational 3E-ECRIS successfully meets the demanding proton beam requirements for both LEHIPA and MEHIPA, demonstrating excellent beam quality with a measured 60% proton fraction and highly refined emittance. To push the boundaries of accelerator capabilities, the ongoing development of multi-cusp sources utilizing permanent magnets and a novel tetrode extraction system promises to significantly reduce emittance while improving overall energy efficiency. With mechanical integration complete, ongoing active plasma measurements on the tunable hexapole assembly will continue to refine beam dynamics, establishing these green, high-efficiency technologies as the standard for next-generation high-intensity proton injectors.

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