ION ACCELERATION IN A COMPACT HELICON SOURCE IN VARIOUS PERMANENT MAGNET CONFIGURATIONS

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Abstract

The parameters of plasma and emergent ion beam were examined in a 4.5-cm-diam compact helicon source excited by a double-turn $m = 0$ antenna and equipped with permanent magnets. The basic magnetic configuration was formed by a radially magnetized cylindrical system assembled of ferrite bars. It could be enhanced by an axially magnetized annular ferrite that was installed near the source outlet to create the magnetic nozzle. The magnetic configuration was found to be a crucial point for production of accelerated ions. At Ar pressures below 1 mTorr, plasma potential in the discharge chamber was as high as 100–120 V, which is by 50–60 V higher than in the drift chamber, but the emergent beam of accelerated ions arose with use of the magnetic nozzle only. This implies that electrostatics might not be the only driver for ion acceleration. At input power of 600 W, the beam of accelerated ions had energies up to 120 eV and the current of 40 mA, and the electron temperature in the discharge chamber was 10–12 eV. The source parameters were optimized with use of various ferrite assemblies and the outlet iron shield, and also of various driving antennas and rf frequencies.
Introduction

Helicon plasmas for electric propulsion and the mechanisms of ion acceleration

Shamrai, Aleksandrov, Bougrov, Virko et al. (1997)
Compact helicon, electrostatic acceleration by external means (grids)

Chang Díaz et al. (1999)
VASIMR – large helicon, ICR + magnetic nozzle acceleration

Boswell et al., Scime et al. (2003)
Intermediate helicons, inherent gridless electrostatic acceleration (current-free double layer, a steep potential drop in a divergent magnetic field at the outlet)

Toki et al. (2003)
Compact helicon, proposal of gridless acceleration with external means: electrostatic (so called Lissajous method) or electromagnetic

Shamrai, Virko et al. (2006)
Compact helicon with permanent magnets, inherent gridless electrostatic acceleration (gradual potential drop in a divergent magnetic field at the outlet)
Helicon Source: Device and Diagnostics

**Chambers:**
- **Discharge chamber:** 4.5-cm-i.d., 32-cm-long quartz tube with a movable end plate (quartz or molybdenum)
- **Drift chamber:** 14.5-cm-i.d. quartz tube

**Magnetic system:** Two axially movable components – CFA and AF

**Rf supply:** 13.56MHz, up to 1kW (or 27.12MHz, 300W; or 40.68MHz, 60W)

**Antennas:** Axially movable $m = 0$ or $m = \pm 1$

**Diagnostics:**
- **Plasma:** axially movable probes (Langmuir or planar with a guard ring)
- **Ion beam:** multi-grid RFEA, 7 cm downstream
- **Thrust:** dynamometer (torsion balance), 10 cm downstream (*not shown*)
Helicon Source: *Magnetic System Components*

I. **Cylindrical Ferrite Assembly** (CFA)
   with radial magnetization

   - Single-layered CFA
   - Three-layered CFA

   \[ \uparrow \mathbf{M} = \text{magnetization directions} \]

   - 12x3.8x1.5 cm Ba-ferrite bars,
     12-cm inner diam, changeable number of layers

II. **Annular Ferrite** (AF)
   with axial magnetization

   - Magnetic nozzle

   - 5.5(13.5)-cm-i.(o.)d., 1.8-cm-wide annular Ba ferrite

III. **Iron Shield** (IS): 25x25-cm, 2-mm thick iron plate with a 4-cm-diam orifice
     installed as the outlet flange
**Helicon Source: Magnetic Field Profiles**

**Cylindrical Ferrite Assembly (CFA)**

CFA: quite smooth field away from the midplane

**Annular Ferrite (AF)**

AF: two strong field cusps behind the ends

**CFA + AF**

CFA + AF: no field cusp between the antenna and strong field area, but outlet cusp remains

**CFA + AF + IS**

CFA + AF + IS: very weak outlet field cusp
Helicon Source: *Driving rf Antennas*

Azimuthally symmetric
\[ (m = 0) \]

Double-turn

Azimuthally asymmetric
\[ (m = \pm 1) \]

Nagoya type III

Double half-turn

Double-turn \( m = 0 \) antenna is the most efficient, both in plasma production and ion acceleration.
Helicon Source: General View

Operation with the CFA
Helicon Source: *Plasma Plume Views*

CFA

CFA + AF

Plasma plume in the drift chamber is well aligned with magnetic field lines.
Emergent Ions: High Ar Pressures

The RFEA faces either to the source outlet ($\alpha = 0^\circ$) or to the drift chamber side-wall ($\alpha = 90^\circ$). Ion-energy distribution function (IEDF) is a derivative of the RFEA current, $F(E) \sim -dI/dV$.

No accelerated ion beam at high pressure, either with or w/o the magnetic nozzle.
Emergent Ions: *Low Ar Pressures*

**CFA**

- $p_{Ar} = 0.8 \text{ mTorr}$
- $\alpha = 0^\circ$

**CFA + AF**

- $p_{Ar} = 0.2 \text{ mTorr}$

The best result w/o the magnetic nozzle $(P_{rf} = 170 \text{ W})$

The best result with the magnetic nozzle $(P_{rf} = 560 \text{ W})$

With the magnetic nozzle and at Ar pressures below 1 mTorr, an emergent beam of accelerated ions arises, with mean energy above 100 eV (relative to ground). Net outlet energy gain is up to 60 eV, and the fraction of accelerated ions can exceed 50%.
Emergent Ions: Effects of End-Plate and Iron Shield

Effect of the back end-plate biasing

Positive biasing of the conducting back end-plate enables to increase ion beam energy up to 170 eV, but net energy gain remains the same, about 60 eV.

Effect of the iron shield installation at the outlet

Installation of the iron shield at the source outlet results in increase of both the ion beam energy, up to 160 eV, and net energy gain, up to 70–80 eV.
Emergent Ions: *Effects of Frequency and Antenna*

The double-turn $m=0$ antenna is the most efficient, both in plasma production and ion acceleration, as compared with the double half-turn and Nagoya antennas. At higher frequencies, the discharge can be sustained at considerably lower rf powers and gas pressures.
Emergent Ions: *To the Origin of Ion Acceleration*

**CFA+AF:** A potential drop at the outlet is an apparent driver for ion acceleration.

Despite strong outlet potential drop, ion beam generation is not observed.

The potential drop at the outlet, in itself, seems to be not a sufficient condition for generation of the accelerated ion beam at low pressures.
Operation with Various Gases: IEDFs and Views

Xenon (A=131)

Krypton (A=84)

Argon (A=40)

Neon (A=20)

Helium (A=4)
Minimum gas pressure, at which stable discharge can be sustained and the most efficient ion acceleration occurs, is lower in heavier gases (with lower ionization potentials).

Mean ion beam energy grows with atomic mass (except for Xe).

Ion beam velocity falls with atomic mass and ranges from 58 km/s, for He, to 13 km/s, for Xe.
A light, 2.5-cm-diam aluminum disk with a perpendicular triangle counterpoise could rotate on 20-µm-diam molybdenum tension wires. Torsional oscillations of the hanger were suppressed by a magnetic damper. Electrostatic effects were inessential as the disk deflection was independent of the potential applied to it.

**Evidence of contribution of accelerated ion beam:** at the same rf power, the disk deflection with the magnetic nozzle is much larger than without it.

At 500 W, maximum pressure force onto the disk is $1.3 \times 10^{-5}$ N.

**Total thrust** is estimated at a few tenths of mN, considering measured ion current density profile.
Conclusions

• The compact helicon source with permanent magnet system that includes the magnetic nozzle can produce the emergent ion beam with mean energy above 100 eV (relative to ground), current density of 1 mA·cm\(^{-2}\), and total current (at Ar pressures below 1 mTorr and rf power of 500 W).

• Positive biasing of the back end-plate and installing of the outlet ferromagnetic (iron) shield gives rise to further increase of the beam energy.

• The use of higher driving frequencies results in some increase of the ion beam energy and enables operation at lower gas pressures and rf powers.

• The reason for ion acceleration with the magnetic nozzle is apparently a gradual potential drop that arises at the outlet and gives rise to net energy gain up to 60–70 eV.

• Without the nozzle, the potential drop also arises but the ion beam is missing; this is not yet understood and is thought to be an evidence of that electrostatics may not be the only reason for ion acceleration.

• Accelerated ion beam arises in all noble gases; its energy increases with atomic mass, and its velocity is reasonable for propulsion applications.

• The total thrust of the emergent Ar ion flux is estimated at a few tenths of mN.
Next Steps

Further optimization of the source, with the object to enhance considerably the output ion current (ideally, by an order of magnitude).
This is expected to raise the thrust and to reduce its power cost (currently, about 1 kW/mN) and to reduce ion energy cost (currently, a few keV/ion).

Near-future experiments

Further adjustment of the magnetic configuration (with use of available and stronger ferrites and ferromagnetic shields), to raise the ion beam current.
Operation at the lower hybrid resonance (with use of stronger ferrites, at a frequency of 13.56 MHz), to enhance plasma production and output ion current by energizing electrons or/and ions.
Use of higher rf frequencies (27.12 and 40.68 MHz), to benefit from operation at lower gas pressures and rf input powers.

Prospective experiments

Direct thrust measurements (need a large chamber).

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