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Modeling of ion extraction from a toroidal Electron Cyclotron Resonance Ion Source

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ABSTRACT

Electron Cyclotron Resonance Ion Sources (ECRIS) progressed to higher and higher ion currents and charge states by adopting stronger magnetic fields (beneficial for confinement) and proportionally higher ECR frequencies. Further improvements would require the attainment of "triple products" of density, temperature and confinement time comparable with major fusion experiments. For this, we propose a new, toroidal rather than linear, ECRIS geometry, which would at the same time improve confinement and make better use of the magnetic field. Ion extraction is more complicated than from a linear device, but feasible, as our modeling suggests: single-particle tracings showed successful extraction by at least two techniques, making use respectively of a magnetic extractor and of $E \times B$ drifts. Additional techniques are briefly discussed.

1. Introduction

Electron Cyclotron Resonance Ion Sources (ECRIS) are well-known electron-cyclotron-heated plasma-based ion-sources for accelerators and various applications ranging from nuclear fusion to industrial ion processing, isotope separation and mass spectroscopy [1]. The typical ECRIS device (Fig. 1a) confines the plasma by means of a magnetic mirror and multipolar (typically hexapolar) field, with the ions extracted at one end of the mirror. Performances (for example, the extracted ion current I for a particular charge state) improved dramatically over the last three decades, as summarized by review articles [2–4]. To a good extent, such improvements are ascribed to the progressively higher microwave frequency ω used for heating, in agreement with the $I \sim \omega^2$ scaling [1]. According to this scaling and to the EC resonant condition, the extracted current improves as B_{ECR}^2, where B_{ECR} is the field evaluated at the location where EC heating takes place. In proportion with ω and B_{ECR}, the maximum field B_{max} used for axial confinement, evaluated at the ends of the magnetic mirror, was also increased, resulting in increased costs and complexity.

In brief simplistic terms, B_{ECR} sets the performances and B_{max} affects the costs, but the latter is about 3 times higher than B_{ECR}, in a conventional linear ECRIS. The reasons for this is axial confinement of particles (apart from a loss-cone in velocity space). By contrast, confinement in a toroidal device does not require such field non-uniformity (in fact, excessive toroidal non-uniformity is actually detrimental to confinement [5]). We therefore propose that a toroidal ECRIS would make a better use of its maximum field B_{max}, because B_{ECR} would be just nearly as high as B_{max}. Equivalently, a lower B_{max} would be sufficient in a toroidal ECRIS to achieve the same target B_{ECR} as in a linear one.

The toroidal configuration is expected to increase the ion confinement time. The ions that normally would be lost in the longitudinal direction in a linear ECRIS remain confined for a longer time, thus experiencing more collisions and —on average— being ionized to higher charge states. An additional innovative element in our proposed toroidal device is the twisting of the hexapolar coils, which further improves confinement, compared with a simple toroidal device.

The paper is organized as follows. The conceptual design of the toroidal ECRIS is described in Section 2. Section 3 enters in more details about the magnetic configuration. Section 4 presents single-particle calculations of how the ions drift in such configuration, and finally Section 5 shows how adding a capacitor or a coil could deform the ion trajectories and lead to their extraction.

2. Toroidal ECRIS design

In its simplest form, a toroidal ECRIS could consist of several linear ECRISs connected in series with each other in a toroidal arrangement (Fig. 1b). This is reminiscent of the ELMO Bumpy Torus

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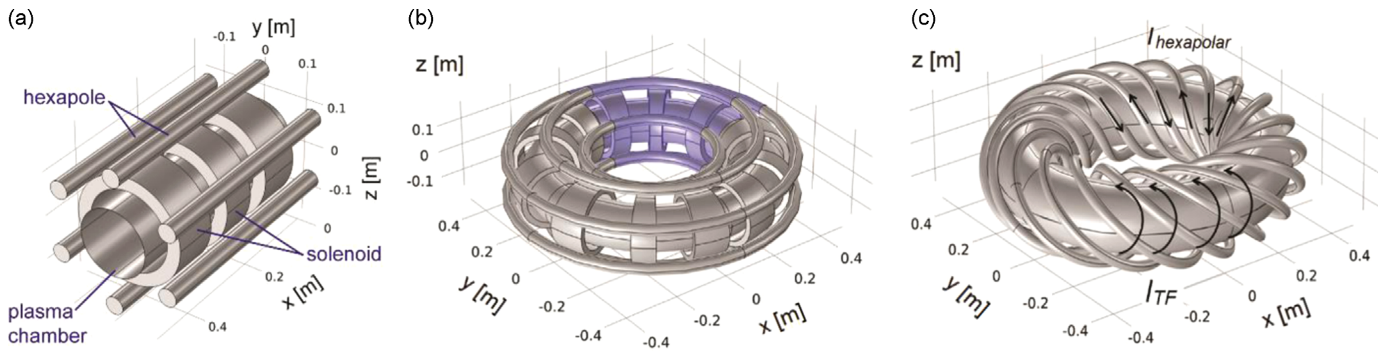

Fig. 1. (a) Schematic view of a linear Electron Cyclotron Resonance Ion Source (ECRIS). (b) Toroidal assembly of several ECRISs connected in series with each other. (c) Similar to (b), except that discrete Toroidal Field (TF) coils are replaced by currents flowing in the poloidal direction in the electrically conductive vacuum vessel, and hexapole coils are helically deformed to generate rotational transform and improve confinement.

fusion experiment [6], consisting of a toroidal array of magnetic mirrors. In analogy with linear ECRIS we could super-impose to the bumpy torus configuration a toroidally curved hexapole field with the goal of improving radial confinement. Such hexapole field could be generated by 6 circular coils, reminiscent of the Poloidal Field (PF) coils in a tokamak, although energized in alternate directions. The PF coils are shown in Fig. 1b, along with several Toroidal Field (TF) coils. An important difference with the tokamak, however, is the absence of toroidal plasma current in this toroidal ECRIS. Therefore, for good confinement we should rather follow the analogy with a toroidal device which has no plasma current, namely the classical stellarator [7], in which the PF coils are now helically twisted (Fig. 1c). This results in the helical twisting of the magnetic field lines, or rotational transform, that helps confinement [7]. Furthermore, we propose replacing the discrete TF coils with a single toroidal coil referred to as "mono-coil", depicted in Fig. 1c and expected to generate no "ripple". In fact, it is proposed that the toroidal vacuum vessel itself can also serve as single TF coil, as in the Madison Symmetric Torus (MST) [8], with added benefits of compactness, simplicity and diagnostic access. To serve all purposes, the vacuum vessel should be made of Aluminum or other highly electrically conductive metal with reasonable stress-strain properties, coated with a plasma-facing material with good resistance to sputtering, such as Chromium.

The metallic vessel should feature a toroidal cut, for instance on the outer equator, filled with an electrically insulating vacuum seal. Biasing the upper outer equator relative to the lower outer equator would result in a current flowing in the vessel in the poloidal direction, generating a magnetic field in the toroidal direction.

To fix the ideas, here we consider a compact tabletop device of major radius 35 cm and minor radius 7.5 cm, with 2 cm thick walls. We examined coil configurations of both types in Fig. 1b and c. For the configuration in Fig. 1c, we have considered hexapoles (6 coils energized in alternate directions, or $l=3$, in stellarator jargon) helically wound with toroidal mode number $n=2$, 3 or 4 and quadrupoles ($l=2$) of $n=3$.

3. Magnetic configuration

3.1. Toroidal field

In the remainder we set the toroidal field to evaluate $B_{tor}=2$ T on the magnetic axis, as this value is intermediate between typical B_{ECR} ($\sim$1 T) and B_{max} ($\sim$3 T) state-of-the-art ECRIS [2–4]. The corresponding frequency for ECR heating at the fundamental harmonic would be a record high 56 GHz. Coil-currents and fields presented hereafter can be easily, linearly rescaled to a different field, $B_{tor} \neq 2$ T, or different frequency, $f \neq 56$ GHz.

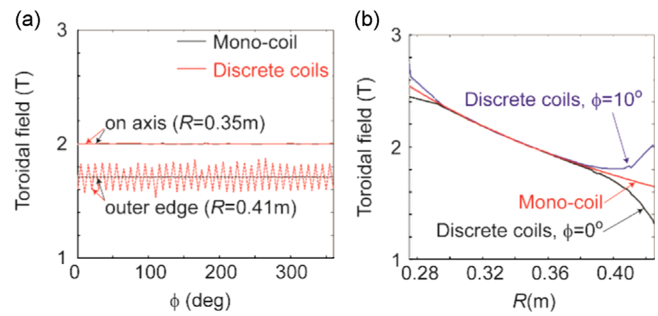

Fig. 2. Illustration of (a) toroidal non-uniformity and (b) radial profile of toroidal field in a device featuring discrete TF coils (Fig. 1b) or whose vacuum vessel acts as a "mono-coil" (Fig. 1c).

A voltage-difference of 0.73 V between the upper and lower outer equators of the vessel causes a poloidal current $I_{pol}=3.5$ MA to flow through it and generate a field $B_{tor}=2$ T in the plasma center. As expected, and as illustrated in Fig. 2, the field is significantly more uniform in the mono-coil configuration depicted in Fig. 1c than in the discrete TF coil configuration of Fig. 1b. In particular, the toroidal ripple is canceled at all locations, including outer radii R where it is normally more pronounced, due to proximity to the coils. Furthermore, in the mono-coil device B_{tor} decays like $1/R$ at all toroidal location. Discrete coils, instead, introduce toroidal non-uniformities at large and small R (Fig. 2b).

Particle tracing calculations showed that these reduced toroidal ripples resulted in reduced particle losses, in agreement with tokamak observations.

3.2. Hexapolar field

The poloidal field B_{pol} is exerted by a set of 6 coils energized in alternate directions (i.e., the current in a coil is opposite to currents in the two adjacent coils), as in a classical stellarator of $l=3$.

The multipolar field creates a magnetic well that radially confines the plasma. Among several possible multipoles, the majority of modern linear ECRIS settled on hexapoles, as a compromise between ion confinement (favored in lower order multipoles) and ion extraction (favored in multipoles of higher order, characterized by a larger area for extraction at the end of the magnetic mirror). Basically the ion confinement needs to be good, for obvious reasons illustrated by the Golovaninski plot [1], but not "too good", because eventually the ions need to be extracted.

For the first toroidal ECRIS we also opted for a hexapole, although helically twisted. The main reason is direct comparison with most linear ECRIS. Considerations on the larger area of longitudinal extraction do not apply to a toroidal ECRIS, where