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Microarticle

Conceptual design of an RF multipole plasma transport and trap loading experiment

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ABSTRACT

A multipole plasma trap uses radio-frequency electric multipole fields to confine the charged particles of a plasma in a 3D volume. For experimentation with this concept, it is necessary to load the trap with the desired distribution of particles. A new concept is illustrated, in which one trap electrode is replaced with the aperture of a linear multipole stage, which acts as a conduit to channel plasma from a source region to the trap volume. This linear multipole plasma transport also lends itself to investigation of 2D multipole confinement, with and without an axial magnetic field.

Introduction

The multipole plasma trap (MPT) approach [1] uses radio-frequency (RF) electric multipole fields to confine plasma particles in a 3D volume, or in 2D about a central axis. The 3D case is similar in principle to the manner in which a Paul trap [2] uses an RF electric quadrupole field to confine small numbers of charged particles, and the 2D case is similar to the use of quadrupoles or higher order multipoles as RF linear traps and mass filters for mass spectroscopy [3] or beam guides. In both cases, the spatially inhomogeneous, time varying field, generally of form $\boldsymbol{E}_0(\boldsymbol{r})\cos(\Omega t)$, leads to a ponderomotive force $\boldsymbol{F}_p = -\frac{q^2}{4m\Omega^2}\nabla \boldsymbol{E}_0^2$ on particles of charge q and mass m that restores them to field minima or nulls. In the adiabatic case $|2(\boldsymbol{a}\nabla)\boldsymbol{E}_0| < |\boldsymbol{E}_0|$ where the particle does not gain significant kinetic energy over the course of a single oscillation at frequency $f_{rf} = \Omega/2\pi$ and amplitude $\mathbf{a}$, the effective mechanical potential that confines particles may be approximated as $V_{eff}(\boldsymbol{r}) = \frac{q^2E_0^2(\boldsymbol{r})}{4m\Omega^2} + q\Phi_S$. The Φ_S term is an electric potential due to space charge and limits the capacity of 2D or 3D RF traps. The MPT approach is conceived to trap quasi-neutral plasma, thereby mitigating space charge repulsion, and is able to achieve orders of magnitude higher particle density (up to the critical density at which the trapped species' plasma frequency approaches the trapping field frequency) [1]. Since higher densities may therefore be trapped at higher frequencies, the property of higher order multipoles to operate at higher frequency makes them desirable for the MPT approach. For example, a 2D multipole of order N (where $2N$ is the number of poles) has effective potential $V_{eff}(r) = \frac{N^2q^2V_{rf}^2}{4m\Omega^2r_0^2}\left(\frac{r}{r_0}\right)^{2N-2}$, where r_0 is the trap radius and $2V_{rf}$ is the potential difference between neighboring poles. An example of particle-in-cell (PIC) simulation (using VSim 9.0 [4] by Tech-X Corp.) of a 3D trap containing quasi-neutral plasma is shown in Fig. 1. The percentage of the trap volume that is essentially free of the external field also goes up with multipole order, leading to a large volume of unperturbed, uniform plasma except where the field becomes strong at the trap boundary. (Further details about the dependence of adiabatic particle trajectories and field characteristics on trap parameters are given in [1] which follows the derivation presented in [5]; the non-adiabatic case is considered in [6].) The large effective trap volume along with space charge neutralization allows an MPT to not only have higher particle density than a single species charged particle trap or non-neutral plasma trap, but also to have much higher total particle count. Furthermore, the physical trap size may be made large compared to length scales of interest in plasma physics experiments, such as $r_0 \gg \lambda_D$ and $r_0 \gg \delta$ (the plasma Debye length and skin depth, respectively [7], noting that these quantities differ fundamentally between ion-electron and pair plasmas [8]). It is therefore necessary to devise a means of loading relatively large amounts of plasma into an MPT.

Typical means of loading an RF charged particle trap include *in situ* methods in which the desired charged particle species are produced in the interior of the trap volume [9]. This can occur for example via an externally produced electron beam ionizing neutral gas in the trap, or

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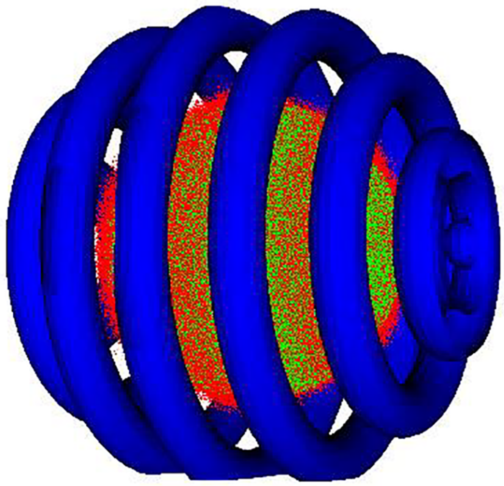

Fig. 1. Particle-in-cell simulation of a 3D MPT with $N = 8$, $r_0 = 10$ cm, loaded with heavy positive particles (green) and light negative particles (red) to simulate quasineutral plasma trapping. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

by photoionization. A source of electrons and ions at the trap boundary, such as thermionic emission from a filament, may also be used. The advantage of *in situ* methods is that the particles to be trapped are born at some depth in the effective potential well and are thus confined by it. Particles to be trapped may also be produced outside the trap and introduced across its boundary, but in this case the effective potential well must be temporarily lowered to admit particles and reestablished once they are in the trap. These existing methods are reasonably suited to transient loading of small bursts of particles (such as by puffing in and ionizing neutral gas), but they are not ideal for steady state operation of an MPT at higher density and particle count. This Microarticle presents a concept that can enable MPT experimentation by introducing a higher flux of plasma species to be trapped than possible with conventional means, in a manner that is compatible with particle trapping in the high-multipole order, large-volume MPT electric field.

Methods and results

An overall view of the concept is shown in Fig. 2, and a detailed side view is shown in Fig. 3. The new approach to MPT loading is based on channeling plasma particles into the trap by means of a linear RF multipole stage. The MPT electrodes comprise a set of rings of constant minor radius but decreasing major radius. The smallest electrode is

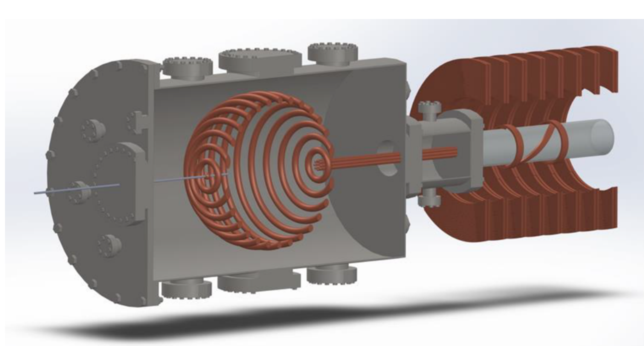

Fig. 2. Cutaway view of the experimental concept showing spherical MPT installed in vacuum chamber. An RF helicon plasma source (at right) produces high density plasma that is channeled by a linear RF multipole stage to the MPT. Details are illustrated in Fig. 3.

approximately hemispherical on the interior surface that it presents to the trap. The end tips of the linear stage replace one of the small MPT electrodes. The new equipotential shape thus created is a departure from the hemispherical one (which is itself an approximation to the ideal hyperbolic shape); however, it has been shown [5] that considerable deviations from ideal equipotential shapes are tolerated without destabilizing trapped particle trajectories. 2D RF linear multipoles of order N are constructed from $2N$ parallel electrodes, whereas 3D RF multipole structures are generally comprised of $N + 1$ electrodes, such that making a hemispherical cut through the electrodes would yield a surface bounded by $2N$ poles. The RF multipole electrodes may be operated in one of two modes in order to attain the needed maximum potential difference $2V_{rf}$ between neighboring electrodes (i.e. between the "even" and "odd" electrodes; see Fig. 3 for an example of electrode numbering): 1) $\pm V_{rf}$, such that when even electrodes are positive, odd electrodes are negative and vice versa; 2) even electrodes receive $2V_{rf}$ and odd electrodes are at the ground potential of the enclosing vacuum chamber. As will be described, the latter method is preferable for the scenario of loading the trap using the linear stage. Also, having a subset of electrodes remain at ground allows easier access for diagnostics. Furthermore, having just one set of high-voltage electrodes simplifies the number of high-voltage feedthroughs and connections; however, the higher voltage standoff of $2V_{rf}$ between RF connections and grounded components must be maintained.

As an example, the MPT shown in Figs. 2 and 3 has been designed (and is currently under construction) with the following parameters: $N = 16$, $V_{rf} = 1000$ V, $f_{rf} = 250$ MHz, $r_0 = 25$ cm, corresponding to a critical plasma density (given by the electron plasma frequency approaching f_{rf}) of $n_{ce} = \frac{4\pi^2 f_{rf}^2\, m\, \varepsilon_0}{q^2} = 7 \times 10^{14}\,\mathrm{m}^{-3}$. The minor radius of the ring electrodes used in this design is 5.5 mm. The end electrode can be replaced by the insertion of a linear octupole ($N = 4$) of aperture radius $r_0 = 10$ mm. The following are a few brief examples of how such a linear stage could be used in this concept. If the linear stage is driven at $f_{rf} = 20$ MHz, $V_{rf} = 200$ V, it can transport H^+ (or H^-) ions with an effective potential well of 10 eV (using the expression for $V_{eff}(r)$ above). If driven at $f_{rf} = 3.0$ MHz, $V_{rf} = 200$ V, the linear octupole can transport Ar^+ with effective potential well 8.5 eV. If an axial magnetic field is added, the ability of electrons to travel along with the positive ions with minimal transverse loss may be investigated, as may be the effect of the magnetic field on the ponderomotive effective potential (including at or around gyroresonance [10]). If the linear stage is driven at the MPT frequency (250 MHz), and if instead of a linear octupole a linear quadrupole is used, with $V_{rf} = 100$ V, electrons are directly trapped with effective potential well 7 eV (and relatively heavy positive ions do not respond to the RF, but are trapped by the electron cloud). In all cases, the RF voltage of the linear stage is small compared to the MPT RF voltage, meaning that the linear stage end tips will still be close to ground potential compared to the high-voltage MPT electrode surrounding them. So that particles enter the MPT at significant depth in the effective potential well, the linear stage may extend a short way past the spherical boundary defined by the MPT electrode surfaces. For example, in the case of the 25 cm, $N = 16$ MPT, an extension of 2 cm into the trap will introduce particles at a location for which the effective potential is less than 10% of maximum.

Conclusions and future work

The RF linear stage affords the opportunity to measure and conduct experiments with particle and plasma trapping in each of the cases mentioned above. The input to the linear stage may be plasma extracted from a helicon source (currently under construction) or other RF plasma source. A configuration in which the RF linear stage and the helicon source operate at the same frequency is possible (e.g. 5–20 MHz range). Fig. 3 shows how the linear stage plasma could be diagnosed by a sight line passing between the electrodes, in a location intermediate to

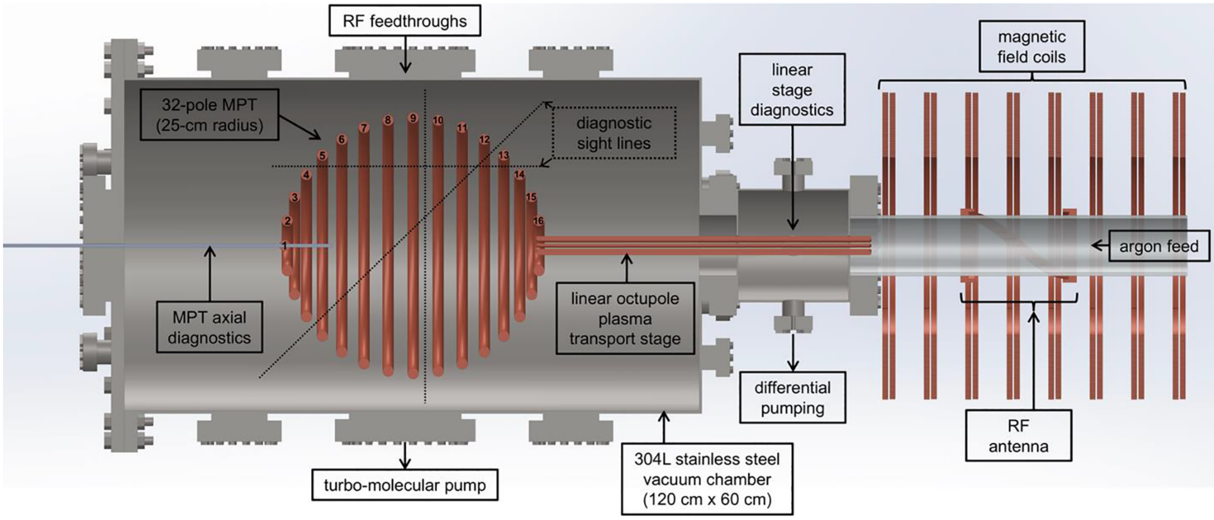

Fig. 3. Side view of cohesive experimental concept comprising helicon plasma source (right), linear RF multipole plasma transport stage (center), and 32-pole multipole plasma trap (left). The main cylindrical vacuum chamber has diameter 60 cm, and is pumped to $< 10^{-8}$ Torr base pressure by a turbo-molecular pump. Several radial and longitudinal ports are available for power feedthroughs or diagnostics, and the MPT may be positioned along the axis accordingly. Differential pumping is utilized in a small module between the helicon source and main chamber to maintain low pressure for the MPT. The magnetic field coils (producing 0–1000 G on-axis) may also be positioned around the small module, and the linear stage may be shortened, such that the linear stage plasma is uniformly magnetized.

the RF plasma source and downstream MPT. A number of diagnostic sight lines (or probe insertion points) are possible for the MPT as well, and the MPT itself can be positioned along the cylindrical chamber axis to optimize access to vacuum chamber ports. The combined platform of 3D MPT and 2D linear stage provides an environment to explore a range of plasma trapping and transport experiments in a practically accessible range of RF parameters, with good diagnostic access in a laboratory vacuum chamber. The addition of an RF plasma source including DC axial magnetic field completes the experimental concept. 3D PIC simulations of MPT performance and 2D simulations of the linear stage are already in progress, with particular attention to the effect of inserting the linear multipole to varying depth past the boundary of the 3D trap.

Acknowledgments

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