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MAGNETO-OPTICAL TRAP CATHODE FOR HIGH BRIGHTNESS APPLICATIONS*

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Abstract

Electron bunches extracted from magneto-optical traps (MOTs) via femtosecond photo-ionization and electrostatic acceleration can have significantly lower transverse emittance than emissions from traditional metal cathodes [1]. Such MOT cathodes, however, have two drawbacks: the need for multiple trapping lasers and the limit to ~ MV/m fields. Designs exist for MOTs which only require one trapping laser [2–4]. Our RF simulations in High Frequency Structure Simulator (HFSS) indicate that the cone MOT is the only one compatible with high gradient RF cavities. We present the combination of the two, an RF cavity with a cone-MOT as part of its geometry. It only requires one trapping laser and can use much higher fields. The geometry of the chamber is compatible with a wide range of MOT species, which allows the search for one which is compatible with copper cavities.

INTRODUCTION AND MOTIVATION

In the last few decades, electron bunches generated by femtosecond photoemission from metal cathodes have enabled such powerful techniques as Ultrafast Electron Microscopy and Ultrafast Electron Diffraction (UED) [5,6]. While these metal cathodes, flat or tipped, remain the industry standard, increasing attention has been put on the photo-ionization of laser-cooled gases, namely those in MOTs, as an alternative [1,2,7].

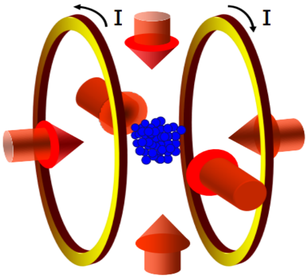

Figure 1: A generic 6-beam Magneto-Optical Trap with quadrupole magnetic field. Reproduced from [8].

Magneto-optical traps traditionally comprise of three orthogonal pairs of lasers which exert radiation pressure on the atoms in the overlapping region (Fig. 1). By the addition of an anti-helmholtz quadrupole magnetic field, the atoms in the trap experience position-dependent Zeeman splitting. This creates a resonance condition wherein atoms that wander further from the center of the trap are more likely to absorb a laser photon, thus establishing a stable trapping condition. If an electric field is then imposed on the trap, it becomes an electron source upon photo-ionization of the atoms [1,2].

Studies of MOT electron sources have demonstrated transverse emittances significantly lower than emissions from metal cathodes. MOTs also have favorable properties for ultrafast operation. For one, they are self-replenishing. As atoms are ionized and discarded, more are captured in the trap. The setup is thus not subject to breakage as metal tip sources are [1,2].

Promising as such MOT electron sources are, they suffer from two common drawbacks. The first is that a traditional six-beam MOT requires multiple trapping lasers and thus laborious optics setups. The second is that existing MOT electron sources can only extract the electrons from the MOT with a DC field [2]. They are thus limited to electric fields that cannot exceed the order of ~ MV/m, and are thus subject to greater beam degradation by spacecharge effects such as disorder-induced heating.

A more preferable solution would then be a MOT electron source which only requires one trapping laser and ~10 MV/m extraction fields, such as those in RF cavities.

CHAMBER DESIGN

MOTs which only require one trapping laser exist [2–4]. The varieties that have the most experimental success and are thus most interesting to our application are the grating, pyramidal, and conical geometries.

The grating MOT works by reflecting an incident beam at an oblique angle from different sides, thus creating an overlapping trapping region in the center [2,3]. Though compact and proven effective in a DC setup, the sharp gratings introduce the risk of arcing in the high-field environment and are not compatible with our goal.

The pyramidal MOT works by reflecting an incident beam inwards with its four sides (See Fig. 2). The beam, once twice reflected, returns along its incident direction [4]. Thus stable trapping is achieved in all three orthogonal directions (up-down and the two lateral sides). We then attach the pyramid to the flat backwall of the design of an existing 1.6 cell RF gun. Since the atoms are trapped in the inte-

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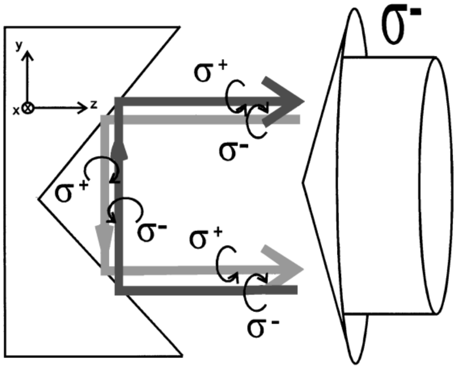

Figure 2: A cross-section of the reflection scheme in the pyramidal and conical geometries. The polarizations are also marked. In both cases no wave plates are needed. Reproduced from [9].

rior of the pyramid structure and are thus approximately where the flat cathode would normally be, the electron trajectories would be generally similar. However, when we solve for the field amplitudes in HFSS, we find that there are non-negligible transverse fields on-axis. The on-axis fields where not affected by decreasing the mesh size. As the cause of these fields are unknown to the authors, we could not simple ignore them. Attempts to perform particle tracking simulations with pyramidal-MOT RF gun's fields also proved unproductive. Hence, we must also reject the pyramidal MOT.

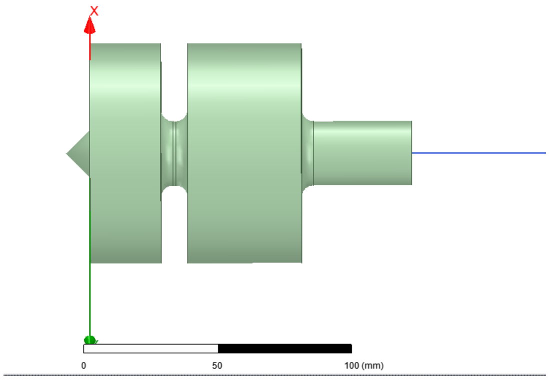

Figure 3: RF Gun with cone-MOT attached. The blue line is the longitudinal axis. The trapping beam is sent down the axis at a small angle. The electrons are accelerated along the axis. The black/white bar is a 100 mm long scale.

The conical MOT is perhaps the easiest to understand. The cone symmetrically reflects the incident beam inwards to provide transverse trapping, then back upwards to provide longitudinal trapping (See Fig. 2). We similarly attach the cone to the end of the RF gun (See Fig. 3). When solving for the fields in HFSS, we also found non-negligible transverse fields on the longitudinal axis, albeit much less intense than in the pyramidal case. However, in this case, due to the cylindrical symmetry, we can conclude that the transverse fields are nonphysical artifacts of the simulation. We now reach our solution: A cone-MOT attached to an RF Gun.

The RF Gun used is one designed by UCLA in collaboration with Radiabeam Technologies for the Fermi Gun II, for the Sincrotrone Trieste (ST) facility [10].

One thing to note here is that copper has a low magnetic permeability, $\mu = 1.26 \times 10^{-6}$-H/m. The quadrupole fields are not strongly shielded by the copper RF cavity.

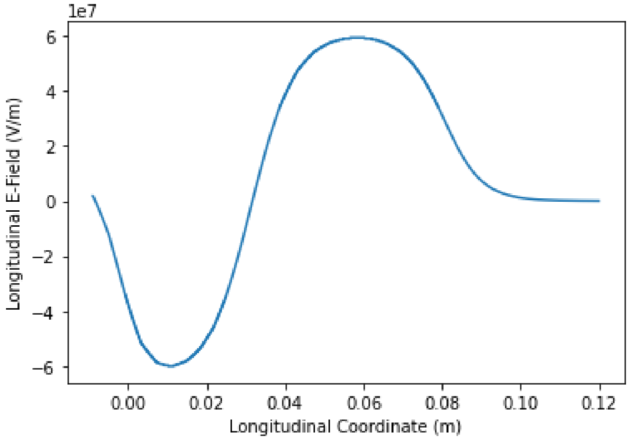

Figure 4: The on axis longitudinal electric field. The left side is the tip of the cone and the right is the exit of the gun.

After solving for the fields, we see in Fig. 4 that the cone perturbs the field we would expect from a normal 1.6 cell gun. However, after tuning the gun such that the eigenfrequency is the correct 2.856-GHz for S-band RF power, we see the perturbation is, in fact, quite subtle. With the longitudinal fields in hand, we extrapolate the transverse fields from it.

While the field amplitudes are correct, we must now scale it to some maximum value. To that end, we note that the highest fields in the chamber are not on the axis, but on the edge of where the cone meets the back wall of the chamber (See Fig. 5).

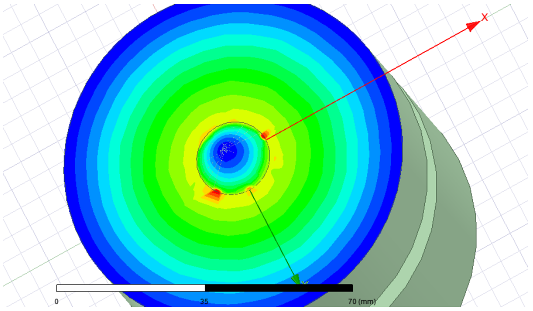

Figure 5: The color map shows that there are spikes in fields on the edge. This was run to illustrate the high fields on the edge. When increasing the mesh density, the cylindrical symmetry becomes more apparent.

Taking the maximum tolerable field as 100-MV/m at the edge, the on axis maximum field would be ≈ 60-MV/m, and thus we scale it to that value.

ELECTRON DYNAMICS

Having obtained the field map of our MOT-Gun, we may now perform particle tracking simulations. The electrons in the trap are pumped by the trapping lasers (To the 5P state by a 780 nm laser, in the most common case of trapped Rb atoms). By briefly turning off the trapping lasers, the atoms return to the ground state. Now, by setting the 780 nm pumping laser and 480 nm ionizing laser to be perpendicular, we can shape our ionization region to be a ~30-µm cross-section region [2, 11]. Based on past experiments, we may extract 1000 electrons per shot at a 1-KHz rate, thus extracting sufficient current for practical applications [2].

We use the photo-ionization emission scheme outlined in Engelen et. al. and perform our simulations in General Particle Tracer (GPT) [12]. The point-to-point space charge algorithm is used. The ions were modelled as stationary point-charges.

The first task is to scan over the phase offsets, ϕ to our RF cavity while tracking a small amount of charge. The longitudinal field at some point varies as: $E = E_0 \cos(\omega t + \phi)$. With the simulation beginning at $t = 0$, only in a window of values for ϕ, the electrons may escape the chamber and not be caught by the turning sign of the fields (See Fig. 6).

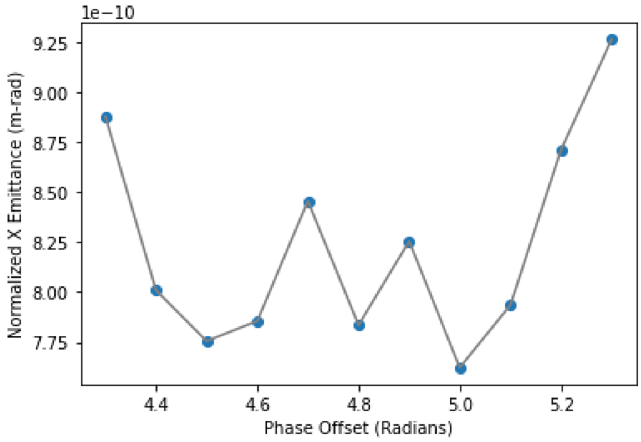

Figure 6: The emittance of the beam is plotted against the phase of the RF field.

The overall rough valley shape of the relation is to be expected. As the phase moves towards untenable values, one would expect that the emittance increases. We choose the local minimum value of the offset $\phi = 5$-rad for all further simulations.

We simulate an electron bunch of 10^3 e^- for different values of distance, Δz from the back wall. We do so because the center of the MOT can be set anywhere inside the cone. At $\Delta z = -0.001$-m and $\phi = 5$-rad we find the minimum emittance of $\epsilon_{nx} = 1.0$-nm-rad. We note that this is lower than the value of 1.9-nm-rad for the 10^3 e$^-$ bunch extracted with a DC field in Franssen et. al.. One may then conjecture that the beam was at low energies for a shorter amount of time and disorder induced heating effects were not as severe.

DISCUSSION AND CONCLUSION

The design put forward in this paper does solve the two problems we posed at the beginning. It requires only one trapping laser and allows extraction of the electron bunches with ~10-MV/m fields. The emittance of the 1000 electron bunch is also lower than analogous DC setups.

However, this design introduces new issues. Elements commonly used in MOTs, such as Rb or Cs, introduce the risk of chamber breakdown at the high RF fields.

Many elements are able to be cooled in MOTs, such as Er, Dy, Rb, Cs, and Li [13, 14]. Further work needs to be done to examine the behavior of such elements resting on copper in high E-fields. The proposed design is not specific to one MOT-species, and is thus compatible with these possible choices.

Additionally, the species of interested need not be MOT-compatible to be laser cooled. The concept introduced here could be applied to other techniques such as Doppler cooling to further expand the possible elements used as an electron source [15].

One possible application of this project is UED. It does have a good value of emittance and temporal resolution ~100-fs. However, the beam has a negative energy chirp (higher energy in front), and is thus not compressible by chicane. An avenue of future work could then be designing a chamber that has a third criterion of producing a positively chirped bunch which could then be compressed to below 100-fs.

There are MOT techniques where one can ramp up the magnetic field and laser power to temporarily compress the MOT cloud [16]. For our purposes the current density is sufficient. However, it may allow us to yield higher currents, or obtain a smaller source size for the same current. It is an avenue of future work

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