On the Possibility of a 10^{16} cm^{-3} Density, 1 Meter Long Plasma for Accelerator Applications

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Abstract

Uniform, high density plasmas on the order of a few meters in length are needed for the next generation of plasma based particle accelerator boosters. Such plasmas are currently beyond the state of the art. In this poster, we present the results of a feasibility study for producing a one meter long, uniform plasma with a density of 10^{16} cm^{-3} by laser ionization based on resonant saturation (LIBORS)[1]. Scaling laws relating plasma density and length, laser intensity and pulse width are found using a rate equation model developed by R.M. Measures et al. The status of initial experiments using a 30cm Lithium column will be presented.

1 INTRODUCTION

Plasmas have been conclusively shown to support incredibly high electric fields that can be used to accelerate particles. In order to obtain a significant particle energy gain however, the length over which injected particles co-propagate with the high space charge electric fields (wakefield) excited in a plasma must be on the order of one meter or more. At present, electron drive bunches have propagated through laser produced plasmas (~10^{15} cm^{-3}) of over 1 meter in length with sufficient energy density to excite a large gradient wake. Using the state-of-the-art electron beam parameters that are available today (1 nC, 100 fs σ_z in the arcs of the SLC) it may be possible to obtain an accelerating gradient of tens of GeV/m over a length of one meter or more if a uniform density plasma source with an electron density of 10^{16} cm^{-3} were available. Such a plasma source is not available today.

Recent breakthroughs made by a UCLA group have made possible the generation high plasma density columns of 1 meter long or greater in length. An extremely uniform column of neutral lithium vapor produced using a lithium oven, was photo-ionized using a UV laser to produce densities of up to 6×10^{14} cm^{-3}. These densities are an order of magnitude greater than those available to-date using other technologies. The UCLA, USC, and SLAC collaboration are currently using such a source in the E162 experiment. However, limitations imposed by damage to optical components, the depletion of the UV photons and the required plasma density uniformity all conspire to limit this method of producing long plasma columns to densities less than about 6×10^{14} cm^{-3}, even though a neutral lithium vapor column with extremely uniform densities of up to 10^{17} cm^{-3} can be produced quite easily over many meters in such a device. An efficient, alternate technique of ionization is therefore needed to reach plasma densities in the range $10^{15} - 10^{16}$ cm^{-3}. A feasibility study has been performed and shows that a spectroscopic technique known as LIBORS (Laser Ionization Based on Resonant Saturation) is the best candidate likely to achieve the uniformity, and the higher plasma densities using metal vapor columns produced by heat pipe ovens.

In the next section, a brief description of the LIBORS theory will be given, followed by a summary of the analytical calculations and finally, a description of the progress on developing a proof of principle

In Phase II we intend to first develop the LIBORS technology to first produce a 30 cm long plasma source in the $10^{15} - 10^{16}$ cm^{-3} density range. This density range corresponds to the frequency of the accelerating wave in such a plasma of 300 GHz to 1 THz range. The second goal would be to build a 1 meter long device and deliver it to an end user such as the E162 collaboration at SLAC.

2 LIBORS THEORY

In the LIBORS process, a long pulse, tunable laser with a photon energy equal to the first excited energy state of a working gas atom is used to ionize the gas through superelastic collisional heating of the gas. The population of laser-excited neutrals represents a reservoir of energy which, via superelastic collisions, is transferred to the initially small population of free electrons. The electrons' interaction with the excited neutral atoms then drives the ionization. Because resonance ionization and superelastic collisions both have large cross sections, the LIBORS process can very efficiently ionize a plasma channel. In Figure 1, we show an energy level diagram of neutral lithium. The energy of the first excited level ($1s^2 2p^1 (^2P)$) represents a significant fraction of the ionization potential. The laser-induced saturation quickly locks the excited state population to 3 times that of the ground state population ($g = g_2/g_1 = 3$). This excited level now acts as a pseudo-ground state with a reduced electron collisional ionization potential. Electrons in this level are collisionally excited to higher bound levels, from which they are rapidly collisionally or photo ionized. Because the collisional excitation (and ionization) rate is proportional to N_e, the electron density, there is positive feedback and once a critical electron density is passed, rapid ionization of the vapor occurs.

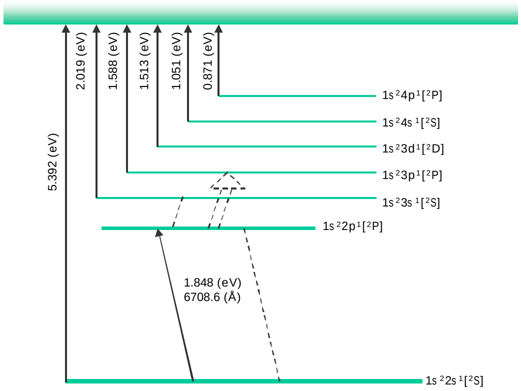

Figure 1: Energy level diagram of the Lithium atom. The first excited state is 1.848 eV above the ground state.

2.1 Calculations

In figure 2, we show the four stages of LIBORS model. One assumption of the model is that the energy, E_{c1} , necessary to ionization the working atom is greater than twice the energy E_{21} between the ground state and the first excited state, and less than the three times that energy, i.e. $2E_{21} < E_{c1} < 3\ E_{21}$. The alkali metals exhibit this property, and we will restrict our discussion to lithium. If the laser radiation is assumed to be suddenly applied at t=0, with a photon energy of $h\nu = E_{21}$, then the subsequent chain of events can be viewed as proceeding in the four stages indicated in Figure 2.

In stage 1, the laser resonantly excites the ground state electrons to the excited state, locking the population densities in the ratio of their degeneracies. For Lithium, this ratio is 3.

In stage 2, there is a rapid growth of free electrons due to two-photon ionization of resonance level and laser induced Penning ionization. The free electron population rapidly gains energy through superelastic collisions. The electrons created by these initial processes rapidly gain energy through superelastic collisions with the laser sustained resonance state population, effectively quenching that state.

In stage 3, the free-electron temperature is viewed as stabilizing as a result of a balance between the rate of superelastic heating and excitation cooling. These electrons now give rise to an exponential growth in the free electron density due to both direct collisional ionization of the resonance level and single photon-laser ionization of the collisionally populated intermediate levels.

Finally, in stage 4, runaway collisional ionization of the intermediate levels occurs once a critical electron density is achieved. This process leads to the ionization burnout that results in almost complete ionization of the laser pumped species. Analyzes indicate that during this rapid burnout phase, superelastic heating is unable to maintain the free electron temperature and a sudden drop in the temperature is expected. Our simple model neglects this effect.

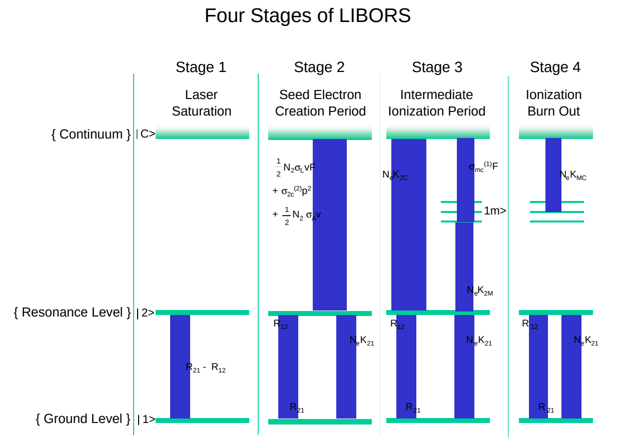

Figure 2: Diagram of the four stages of laser ionization based on resonant saturation (LIBORS). Stage 1: The laser rapidly locks the ground and the resonance-level populations in the ratio of their degeneracies. Stage 2: (i) Rapid growth of free electrons due to two photon ionization of resonance level and laser induced Penning ionization. (ii) Free electrons rapidly gain energy through superelastic collisions. Stage 3: (i) Direct electron-impact ionization of resonance level and single photon ionization of collisionally populated upper levels dominate the rate of ionization. (ii) Electron temperature stablizes as the rate of superelastic heating balances the rate of collisional cooling through excitation. Stage 4: (i) Runaway collisional ionization of upper levels occurs once a critical electron density is achieved. (ii) Superelastic heating can no longer balance collisional cooling and the electron temperature falls.

Figure 3 shows the burnout time (i.e., the time when full ionization is reached versus laser intensity for the three different neutral densities considered here. Notice that at the higher electron densities and laser intensities, the burnout time is achieved within tens of nanoseconds. This characteristic is important when determining the

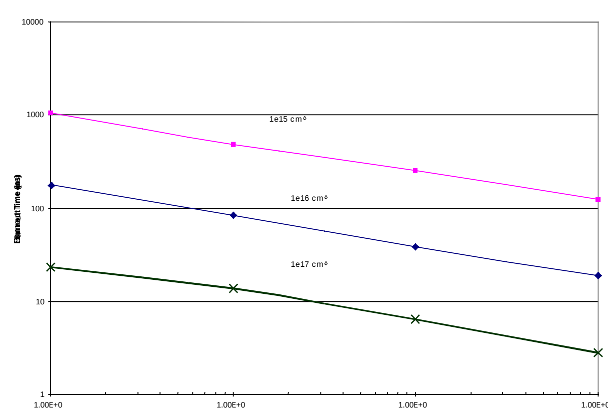

Figure 3: Ionization burnout time versus the incident laser intensity. Contours are results for three different neutral densities 10^{15}, 10^{16}, 10^{17} cm^{-3}.

appropriate laser parameters needed to perform a proof of principle experiment.

The current state of the LIBORS computer program does not predict the length of the plasma column formed given a specific laser intensity. This sophistication will be eventually added to the program. Currently, it is sufficient to point out that several authors have found the LIBORS scheme to be 10%-40% efficient. Using 5.36eV as the ionization potential for Lithium, which implies the laser must have between 2.1 to 8.6 J/cm^2 to ionize a 1 meter long column at 10^{16} cm^{-3}.

2.2 Progress of Proof of Principle Experiment

A proof of principle (POP) experiment is currently being set up in the laboratory of a small company called Betadot. The goal of the POP experiment is to first valid the theoretically predicted plasma densities and uniformity using a scaled down Lithium oven of only 25 centimeters in length. As stated in the last section, to produce a plasma column 25 cms in length requires a fairly modest laser system. In this case, a flash lamp pumped dye laser tuned to emitted light with a wavelength of 670.8 nm, the wavelength of the first excited state of lithium. Figure 4 depicts the Lithium oven experimental setup.

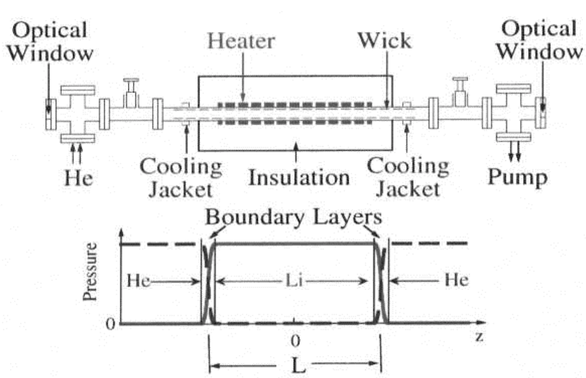

Figure 4: Cartoon of the experimental setup of the Lithium oven. Bottom graph shows the expected longitudinal neutral lithium density profile.

The Helium buffer gas prevents the gaseous lithium from reaching the optical windows and also regulars the pressure of the lithium. Diagnostic measurements have been made to determine the uniformity of the neutral Lithium vapor. Figure 5 shows the results of measuring the temperature of the oven longitudinally. Notice that the temperature profile is uniform longitudinally except at the ends. The corresponding neutral density, as measured by white light absorption and Hook's method is shown in fig. 6. Notice the density is fairly flat (<10%) from 0 to ~11 cm.

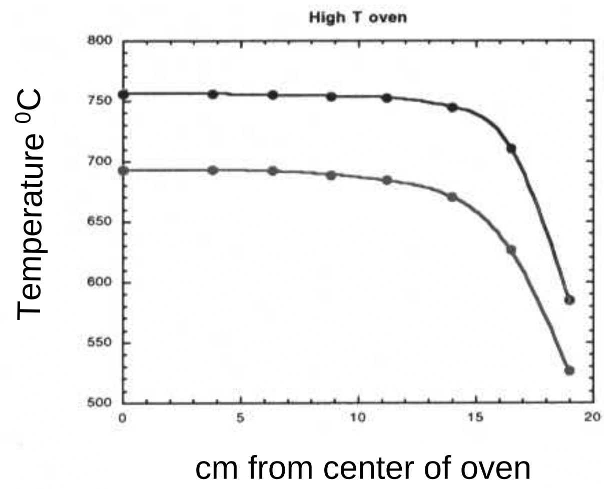

Figure 5: Measurement of the longitudinally along the oven axis. The two lines are for different heater power input.

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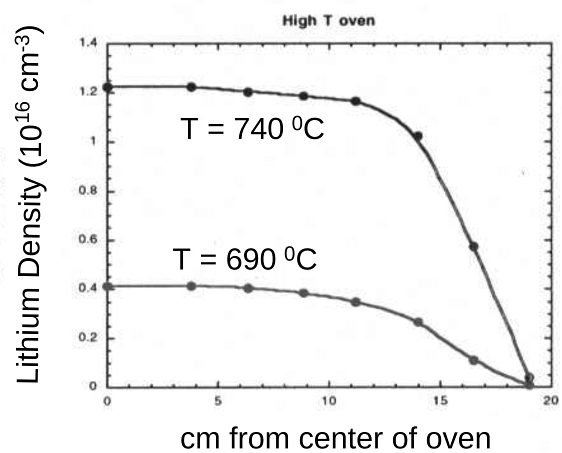

Figure 6: Neutral Lithium density versus longitudinal distance from the center of the oven for two different power/temperature settings.

3 CONCLUSION

In conclusion, producing a long, uniform plasma column is challenging, and necessary for the future generation of plasma assisted particle accelerators. It was shown in section 2 that for a reasonable amount of laser energy tuned to the first resonance state of Lithium, a ~100% ionization is possible, thus producing Lithium plasmas of high density and uniformity. Preliminary measurements on a neutral Lithium oven have been made, and have shown that an oven has the desired uniformity characteristics. Further experimental is planned as the flash lamp pumped dye lasers become operational.

4 REFERENCES

[1] R.M. Measures and P. G. Cardinal Phys. Rev. A, V23, No. 2, p804, 1981