LOW EMITTANCE BEAM EXTRACTION FROM LASER-DRIVEN MULTICHARGED ION SOURCES

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Abstract

Most multi-charged ion sources produce a wide spectrum of charge states, which may make it hard to obtain enough current after selecting a particular state. A newly proposed type of multi-charged ion source has several potential advantages over existing types. The basic principle is that multi-photon absorption in an intense uniform laser focus can give multiple charge states of high purity [1]. Thus, charge state separation downstream is simplified or made unnecessary. Another advantage is that currents of many amperes can be extracted if required. This type of source could be used for heavy-ion fusion drivers or storage ring injectors. There are also industrial applications such as materials processing. Previously, we modeled direct extraction from a spherically expanding laser plasma [2]. We showed that very large currents can be extracted with low ion thermal velocities but that the required focusing system was bulky. The present paper considers compact alternatives, using a conical guide field or a magnetic bucket. Large currents, as required for heavy-ion fusion, are extracted in two stages: a multiple-aperture pre-accelerator is followed by a high perveance single-aperture diode. Our scheme is designed to give low aberrations and low emittance in the combined beam.

1 INTRODUCTION

Our multicharged ion extraction scheme is based on an ion production method [1-3] which uses a petawatt-class short pulse laser for field (tunnel) ionization. This can generate a useful number (10^{12}) of ions in essentially a single charge state. Charge purity is facilitated by choosing a charge state near a shell jump, e.g., Xe^{26+} with ionization energy 860 eV for the 26th electron and a significantly higher value of 1500 eV for the 27th. We also consider Xe^{8+}, with energies 121 and 213 eV.

Section 2 discusses the main challenges: (a) keeping the ion temperature and momentum spread small, (b) avoiding subsequent degradation of charge state due to recombination and charge-exchange with background gas, and (c) producing a useful low emittance beam. We are considering two schemes for connecting the laser ion source with the ion extractor. The first, appropriate for the case of Xe^{26+}, is illustrated in Fig. 1; the second is discussed in Section 3.

The beam emittance depends on both the extracted ion temperature (Section 2) and the extraction optics (Section 3). In applications such as heavy-ion-driven fusion, where the perveance is large, the distance from the extraction electrode to the ion source may be less than the diameter of the extraction aperture. As is well known, aberrations are produced near the beam edge; the outer part of the beam is over-focused and beam emittance may be greatly increased. In our scheme (Section 3), we eliminate this effect by using two-stage extraction, dividing the first (low-energy) stage into a number of annular segments. The beamlet in each segment is initially steered in such a way that all the beamlets are parallel when they arrive at the exit of the high-energy second stage. Thus the usual S-shaped emittance diagram is straightened. In Ref. [4] we

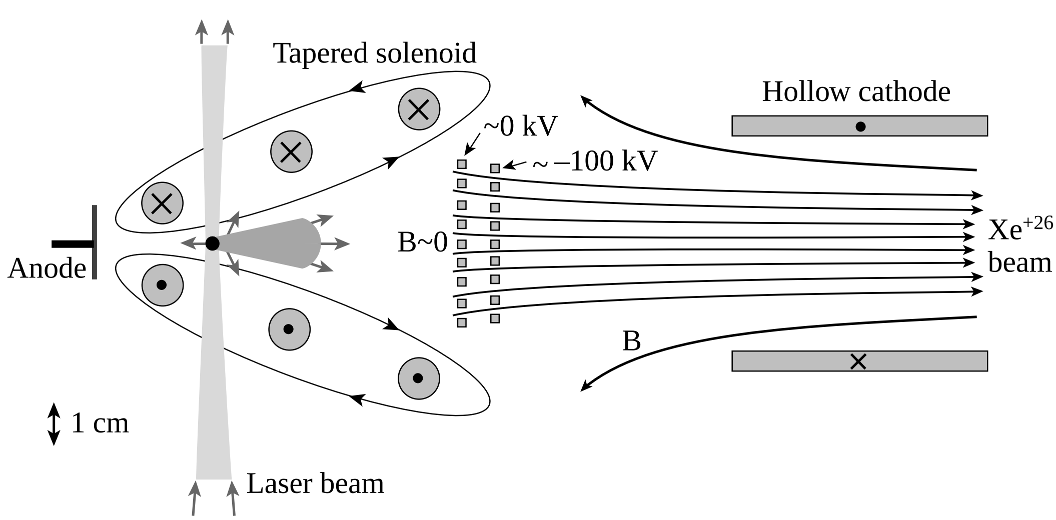

Fig. 1. A conceptual method of extracting highly-charged ions created by a short-pulse laser. Frozen Xenon targets ~10 µm in radius are prepulsed by a low energy laser and expanded well below the critical density before the main pulse. Typical numbers for the main laser: 0.5 µm, 100 fs, 1 petawatt. The tapered solenoid field directs ion flow toward the concentric annular extractor grids, which are adjusted radially to control beam aberrations.

consider the effect of gaps between beamlets, with space charge producing radial velocities, and show how to make the resulting emittance growth small compared with the thermal emittance in practical cases.

2 ION PRODUCTION CONCEPT

The key features of the concept depicted in Fig. 1 are: (1) Injected targets are illuminated within a super-gaussian laser focal spot such that all atoms see a uniform laser intensity and all reach the same charge state by field ionization. (2) A tapered (conical) magnetic solenoid adiabatically converts transverse ion motion during plasma expansion into parallel ion motion towards the extractor grids. (3) An anode plate is biased after expansion of the target laser plasma to joule-heat plasma electrons and prevent recombination; it also controls the plasma floating potential and gates the ion extraction through the grids. (4) A set of small annular ion extraction grids is offset to correct for beam aberrations in the high voltage ion diode.

In the example shown in Section 3, the laser intensity is chosen to produce Xe^{8+}. For other applications, higher charge states are needed. A recent calculation by Todd Ditmire [3] gave the laser intensity to optimize the field ionization production of Xe^{26+} using a 400 fs pulse at 0.5 μm wavelength, corresponding to a frequency-doubled Nd: glass Petawatt CPA laser. The optimum laser intensity 10^{19} W/cm^2 produces >99% charge state purity; $4 \cdot 10^{18}$ W/cm^2 gives 45% purity with the rest in lower charge states; and $2 \cdot 10^{19}$ W/cm^2 yields 82% with the rest at 27+ or higher. We conclude that for 90% purity, the focal spot intensity needs to be uniform within ±20%. Because of the small size of the pellet and the extremely short time scale, laser beam filamentation does not appear to be significant; further simulation studies are in progress.

The laser intensity required for a given ionization level depends weakly on wavelength, while the initial electron temperature scales roughly as λ^2. The temperature at the optimum intensity was calculated to be ~800 eV. For laser wavelengths much longer than 500 nm, T_e could be large enough to cause significant impact ionization of the remaining M-shell electrons, but not at 500 nm with reasonably low densities.

Our primary concern is to prevent a significant fraction of the initial electron energy from being transferred to the ions before they are extracted into a beam. While the laser does not directly heat the ions significantly, the hot electrons can collisionally heat the ions during the high density period before much expansion occurs. Also, as the hot electrons expand, they pull the ions along, imparting ordered motion which could be randomized by multiple reflections of the ions in the case of a confining magnetic bucket.

The latter consideration led to the concept shown in Fig. 1. The solenoid field is tapered so that the laser plasma, which is of high magnetic Reynolds number, is adiabatically guided in the later phases of the expansion into predominantly parallel ion motion. Other techniques that can reduce the electron temperature and ion velocity are discussed in Ref. [3].

The plasma volume expansion ratios are of the order of 10^6 to fill the plasma plenum volume shown in Fig. 1. By the ideal gas law (neglecting any recombination and radiation) pV^{γ}=const or $TV^{\gamma-1}$=const. Taking γ=5/3 gives $T \sim V^{-2/3}$ so the electron temperature drops by a factor $\sim 10^4$. In fact, a 1-D radial expansion model in Ref. [3] shows that recombination will occur when Te drops below a few eV without some auxiliary heating. During the latter part of the plasma expansion, a long-wavelength laser or a discharge current could keep Te above a few eV.

3 TWO-STAGE EXTRACTION WITH NULLED ABERRATION

From Section 2, we conclude that the conical adiabatic expander of Fig. 1 would be needed to maintain low ion temperature in the case of Xe^{26+}; on the other hand, for Xe^{8+} the laser power and the resulting electron temperature would be much lower and it would be practicable to capture the ions in a magnetic bucket. In either case, a high perveance beam could be produced. We show here how the usual problems of aberration and emittance increase can be obviated.

The extraction grids are shown schematically in Fig. 2, along with the extraction end of a magnetic bucket source. The grids are annular and are supported by radial spokes.

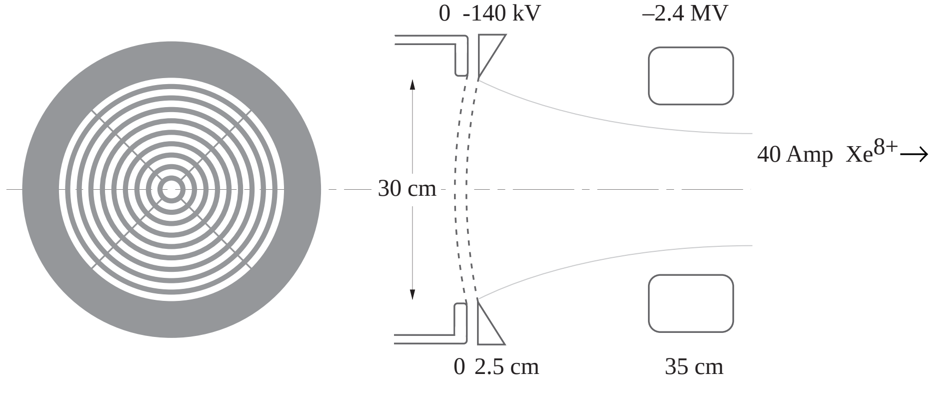

Fig. 2. High perveance extractor concept for laser ion source with magnetic bucket, showing concentric annular grids.

For a typical short-pulse, small heat load system, the spokes are thin with little effect on the beam optics. After the beamlets leave the second set of grids, they enter the high-voltage diode. In the high-perveance case shown, the gap length is comparable to the overall diameter. In a conventional one-stage diode extractor, the resulting large aberrations could be reduced—but not eliminated—by careful shaping of the Pierce electrode and the acceleration electrode. In practice, the outer beamlets are still overfocused, giving the well-known S-shaped emittance diagram. We propose to eliminate this in our two-stage design by appropriate steering of the individual beamlets as they enter the main gap.

Figure 3 shows the extraction grids in more detail. As drawn, both the innner and outer grid rings are arranged at regular intervals, there is no beam steering, and the outer beamlets will be overfocused in the main gap. However, if some of the largest rings are appropriately displaced, those beamlets will receive an outward kick such that all the beamlets will become parallel at the exit of high voltage diode. The required radial ring displacement can be estimated from a standard formula [5]. Fine tuning could be accomplished by axial shimming of the outer rings. Typical radial and axial displacements will be determined by computer modeling. Small steering voltages could also be applied to the rings for fine tuning.

3.1 Computational Plan

We will model the system shown in Figs. 2 and 3 using the self-consistent Trak code, as in Ref. [2]. We plan several stages of modeling.

In the first, simplified, stage, the beamlets are launched at the preaccelerator exit with the appropriate energy.

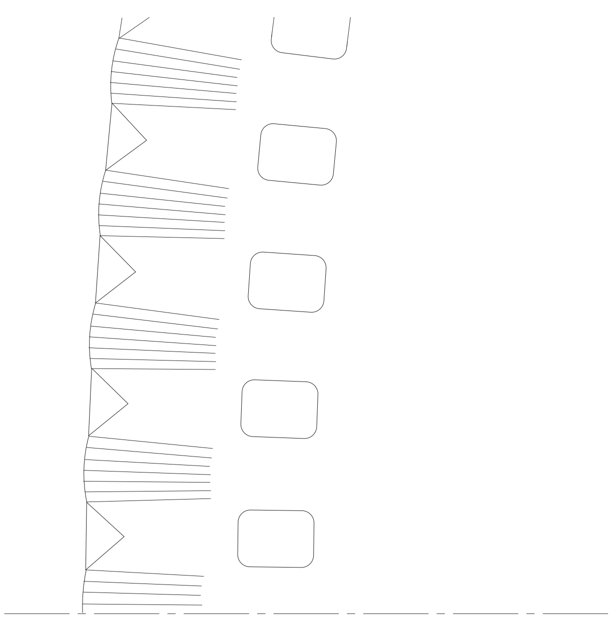

Fig. 3. Model for concentric annular preaccelerator grids.

With this model we can straighten the S curve and study ways to reduce the *merge velocity*, discussed below. The procedure is to: (1) adjust current, voltage, or spacing for approximately parallel beamlets; (2) reduce aberrations by optimizing the curvature of preaccelerator array, the angle of the large Pierce electrode, and the shape of the hollow cathode entrance; and (3) eliminate residual aberrations of the whole array by steering of the beamlets.

The second stage will model the low perveance beamlets separately and minimize their individual aberrations by careful shaping of the electrodes.

In the third stage, the complete system with low-aberration preaccelerators and null-aberration main diode will be modeled. We will study downstream space charge expansion into the gaps between beamlets and look for ways to minimize the resulting emittance growth. This emittance is proportional to the expansion velocities of the beamlet edges at the time of merging. There are several factors that reduce the merge velocities. The driving space-charge force can be reduced by higher preaccelerator energy or using a larger number of beamlets. The merge velocity is also reduced by reducing the ratio of gap width to beamlet width at the preaccelerator exit. This ratio could be made very small by using three-grid preaccelators. We can also look at other effects, such as overfocusing the preaccelerators or increasing the acceleration gradient downstream, which might reduce the merge velocity.

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