Hypervelocity dust beam injection for internal magnetic field mapping

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Abstract

Injecting neutral atoms into high temperature plasmas forms the basis for several important diagnostics, such as Motional Stark Effect (MSE), and charge exchange recombination spectroscopy (CERS). We describe an alternative approach to seeding the plasma with neutrals, via 'hypervelocity dust beam injection' (HDBI), using micron-sized dusts. Among its many potential applications, HDBI mapping of two-dimensional internal magnetic fields inside medium sized (50-500 eV) plasmas is discussed in detail. Electrostatic acceleration at $\sim$ 100 - 200 kV will launch a stream of (0.2-10 μm sized) dust grains of lithium or carbon to hypervelocities (1-10 km/s). Each dust grain, acting as a 'micro-comet' in the plasma, forming a plume (tail), which if photographed, will reveal the direction of the local magnetic field, with anywhere from 10-100 microcomets in the plasma at any time, a full profile of B-field direction could be obtained per high resolution image. Due to the small dust grain size, the perturbation to the plasma will be minimal. HDBI could be a simple, low cost approach to obtain internal magnetic field information in plasmas with magnetic field structures that are significantly different than vacuum fields, such as in spherical tokamaks, FRC's, RFP's, and spheromaks.

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I. INTRODUCTION

Through their interaction with plasma electrons, ions, and confining magnetic field, neutral atoms inside high temperature plasmas can provide critical diagnostic information about their surrounding. These neutrals forms the basis for several key fusion plasma diagnostics, including Zeeman spectroscopy and motional stark broadening (usually known as MSE) for measurement of internal magnetic field and current density distribution [1–5], and charge exchange recombination spectroscopy (CERS) for measurement of ion temperature profile and plasma rotation [6–8]. All these diagnostics are based on one of the two methods to deliver neutrals to regions far away from the plasma boundary, namely, neutral beam injection (NBI) and pellet injection (PI). Popular as these methods are, there are several well known issues associated with NBI and PI, which make them non-trival for diagnostics.

Complexity associated with NBI can be directly traced back to its ion-beam origin. Ion beams have low particle density because of the Child-Langmuir limit. Therefore, NBI diagnostics can not achieve sub-ms time resolution (time less than 1 ms means too small signal-to-noise ratio for NBI diagnostics) [9,10]. Ion beams do not penetrate the magnetic field of a high temperature plasma, therefore, a neutralization cell is necessary. Furthermore, high energy and long time operation of diagnostic NBI can produce substantial plasma perturbation, in particular, rotation. PI is proposed for fusion plasma fueling [11], but when used as a diagnostic, substantial plasma perturbation results, including plasma cooling and current profile modification leading to disruptions.

We propose a micron-size 'dust' based neutral injection method, which we call hypervelocity dust beam injection (HDBI), as an alternative to NBI and PI for high temperature plasma diagnostics. HDBI has many attactive features compared to NBI or PI. We show why HDBI can be a useful alternative to NBI and PI. Among its many diagnostic applications, we discuss in detail the use of HDBI for 2-D mapping of internal magnetic field inside a-few-hundred-eV plasmas.

The article is divided into the following sections: In Sec. II, the unique properties of hypervelocity dusts that are relevant for plasma diagnostics is discussed. Other physical consideration such as dust penetration distance as a function of dust size, velocity and plasma parameters is also presented. These discussions and results form the physical basis for using HDBI as a photon emission source for plasma spectroscopy and 2-D magnetic field mapping. In Sec. III, the fully integrated design for HDBI apparatus is discussed. Function of each part and expected results are also included. Summary and conclusions are in Sec. IV.

II. PHYSICAL BASIS OF USING HDBI FOR PLASMA DIAGNOSTICS

Dust is a ambiguous name for small particulates that can range from sub-micron to mm in size. In this context, we refer it to particulates ranging from 0.1-10 micron in radius (or equivalent for non-spherical objects) specifically. It seems that dusts less than 0.1 micron in radius or equivalent are little different from single atom and nanometer clusters in their interaction with high temperature plasmas, while ones larger than 50 microns have to share same schemes (gas gun, rocket propulsion) for their acceleration to hypervelocity.

Dust penetration of tesla-magnetic-field and electrostatic acceleration are two important aspects of the HDBI. The underlying physics is the dust-interaction with electric and magnetic field; the key parameter is the charge-to-mass ratio. Unlike fundamental particles, such as an electron or a proton, the charge-to-mass (Q_d/M_d, subscript d stands for dust) ratio of a dust is not a fixed quantity. Limiting values for Q_d/M_d is determined by its intrinsic material properties, most notably field emission of electrons [12]. For spherical dusts, the field emission limited Q_d/M_d is equal to $(\epsilon_0 E/\rho)(3/R_d)$ [13,14], where $\epsilon_0 = 8.84 \times 10^{-12}$ F/m is the vacuum permittivity, E is the limiting electric field at the surface dust, ρ is the dust mass density, and R_d is the dust radius. The term $(\epsilon_0 E/\rho)$ is the intrinsic property of a dust, which does not vary with dust size. Typically E is in the range of 10^9 to 10^{10} V/m. We propose to use the electrostatic method to accelerate charged dusts to hypervelocity. From these numbers and using density data for C and Li, one can show that for 5 micron Li or C dusts, electrostatically accelerated dust can move with hypervelocity that falls into the range of 1 - 10 km/s for voltage of 100-200 kV. Dust gyroradii exceed 10 m for 1 Tesla field. Therefore electrostatic acceleration method is adequate to generate hypervelocity charged Li and C dusts, and these charged dust are not affected by Tesla magnetic field, which is common for high temperature plasmas.

The unique feature of the HDBI as a neutral source is better illustrated in Fig. 1, in which characteristic particle composition (number of particles per blob) and neutral velocity are compared for NBI, PI and HDBI. At one extreme, NBI is based on charge-exchange-generated neutral atoms. For effective penetration into high temperature plasmas, the neutral atoms usually have 100 keV or so kinetic energy, which corresponds to $\sim 3 \times 10^6$ m/s velocity for deuterons. For other types of neutral atoms, their velocities are less depending on the atomic mass. At the other extreme, PI are based on macroscopic (mm or larger) pellets, which are usually accelerated to $\leq 5 \times 10^3$ m/s using gas guns. For a Li pellet of 5 mm in radius, the total number of Li atoms is 2.4×10^{22} per pellet, the total number of atoms per pellet is comparable to total plasma ion inventory (equal to number of ions within a 240 m^3 of plasma at 10^{20} m^{-3} density). It's not surprising that PI can strongly change the local plasma density and cause disruptions. Differences between NBI and PI are dramatic: Three orders of magnitude in velocity, and even more orders of magnitude in number of particles per blob. It's only natural for us to propose HDBI which situate in-between these two extremes in the two dimensional space of velocity and particle number.

One certainly can not rule out other possibilities of high velocity neutral sources that are either smaller or larger than the proposed hypervelocity dusts. The other constraint seems to be applicable acceleration methods. It's well known that neutral acceleration is far more difficult than charged-particle acceleration. Based on our discussion earlier, hypervelocity micron dusts can be generated using the electrostatic method, while larger dusts can not be electrostatically accelerated effectively. Objects smaller than micron dust can be electrostatically accelerated to hypervelocities, yet their penetration of the magnetic field can be an issue similar to one facing NBI. Therefore, other neutral source can be developed provided that one can have effective way of acceleration, or that large velocity is not necessary.

Next we show the results of dust penetration into a plasma. The basic process involves evaporization and sublimation of atoms residing on the dust due to the plasma electron heating. Similar models were developed for mm-size and larger pellets [11,15]. The number of particles left within the dust (N_d) as a function of distance into the plasma (r) is given by

$$\frac{dN_d}{dr} = -\frac{4\pi R_d^2 q_\infty f_S}{E_0 + \Delta H_0} \frac{1}{U_d}, \tag{1}$$

where R_d is the dust radius at the distance r into the plasma, q_∞ is the electron heat flux ($= 0.25 n_e v_e k_B T_e$) far away from the dust, E_0 and ΔH_0 represent the binding energy and sublimation energy, and therefore they are material properties, $0 < f_S < 1$ is a shielding factor, and U_d is the initial dust velocity entering the plasma. Drag on dust motion is neglected, therefore a dust always moves with U_d inside the plasma. An important difference between a conventional mm-size pellet and the dust considered here is in the factor f_S, which is ~ 0.3 in the conventional case due to cooling clouds that reduces electron heat flux. For dusts, however, due to the electrostatic charging, substantial voltage can develop on the dust surface, which can repel and reduce the electron flux substantially. The limiting voltage at the dust surface is given by $V_d^{max} = ER_d$, which corresponds to ~ 1 kV for a one micron dust. V_d^{max} can exceed a plasma temperature of a few hundred eV. When electrostatic shielding is included, f_S is calculated as a function of position based on the plasma temperature and density distribution. In the mean time, since the dust is so small, the conventional cooling cloud effect is neglected in the present calculation.

The bottom panel of the Fig. 2 shows the number of atoms left within the dust as a function of distance to the plasma core for a initial 7-micron Li dust. The dust enters the plasma from the edge of a plasma with $U_d = 2$ km/s. The plasma temperature and density profile are assumed to be $T_e = T_{e0}[1-(r/a)^2]^{1.5}$, and $n_e = n_{e0}[1-(r/a)^2]^{0.5}$, where a is the minor radius, a minor radius of $a = 0.5$ m is assumed. The peak temperature and density are assumed to be $T_{e0} = 200$ eV, and $n_{e0} = 1.0 \times 10^{20}$ m^{-3} respectively. Normalized electron temperaure profile T_e/T_{e0} and electron density profile n_e/n_{e0} as a function of the normalized minor radius r/a are shown in the top panel of the Fig. 2. For comparison, dust penetration with and without the electrostatic shielding effect are shown in the bottom panel of the Fig. 2. From Fig. 2 and similar calculations, we conclude that hypervelocities in the range of 1-10 km/s are adequate for significant number of neutral atoms within a dust to reach the center of a few-hundred-eV-temperature, 10^{20} m^{-3}-density plasmas. Another observation is that electrostatic shielding can increase the dust penetration distance into high temperature plasma substantially for fixed dust velocity. In other words, for the same penetration distance, electrostatic shielding can reduce the initial dust velocity requirement.

III. APPARATUS AND EXPECTED RESULTS

A schematic design for HDBI is shown in Fig. 3. The key components of a HDBI include a dust disperser unit, a dust charging unit, an acceleration unit, a dust steering unit, and a dust beam characterization unit. Design consideration and functions of each unit are explained in Sec. III A. Uses of HDBI for 2-D internal magnetic field pitch angle measurement is detailed in the following subsection.

A. Description of a HDBI

The dust disperser unit is used to distribute a controlled number of size-selected dusts to the charging unit. The charging unit is for charging the initially neutral dusts to charge-saturated state (or maximal charge state). A number of designs for dust dispersers can be used to launch dusts into the charging unit [16,17]. We prefer the design by Sheehan *et al.* because of its flexiblility in size selection ranging from 0.5 μm up to several hundred μm, and maximum drop rate of 10^7 dusts per second [16]. A dust mixture of different sizes are initially stored in the Al dust-dispersing cell. In operation, the dispersing cell is shaken by high-frequency (5-80 Hz), pneumatic driver powered by pressured N_2 (10-40 psi). Gravity pulls the dusts down through a series of fine filtering screens which only allow dusts less than the diameters of the screen holes to pass. To begin with, one can use commercially available fine graphite grains for C dusts. Due to the chemical reactivity of Lithium in air, one may have to use certain chemically inert fine grains of Li compounds, such as Lithium deuteride (LiD) for Li dusts.

The charging unit is critical for achieving hypervelocities of 1-10 km/s, since the final kinetic energy of a charged dust is proportional to the number of charges on the dust surface. Both ion beams(i-beam) and electron beams (e-beam) can be used for charging. An e-beam is much more simpler than an ion beam. However, theoretical charge-saturation limit using the i-beam (positively charged dusts) can be ten times more than the e-beam (negatively charged dusts). There is no obvious reason not to believe e-beam can charge the dusts to its negative charge-limit, so e-beam seems to be the preferred choice. In either case, the e-beam or the i-beam intensity can not exceed the Child-Langmuir limit, which corresponds to $2.36 \times 10^{-6} V^{3/2}[\mathrm{V}]/L^2[\mathrm{m}]$ A/m^2 electron/ion emission density. For a 10 keV e-beam (the beam energy should be large enough to overcome the repulsive electric potential $\sim$ 1 kV of the charged dust, yet small enough so that electrons can be stopped by the dust), the electron flux reaching a micron radius dust is $\sim 10^6$ e$^-$/s or more if the e-beam electrode spacing is $L \leq 0.1$ cm. So $\sim$ 1 sec charging time would allow the dusts to reach the charge satuation state. Heating due to the charging process can be neglected. For 1 sec, gravity can pull the dust out of the e-beam path. Relative electric potential may be supplied between the dust disperser and a conducting plate below to compensate the gravitational pull on the dusts, so that the dusts always stay in the e-beam path. Charge-satuated dusts can be kicked out of the charging unit by a pulsed electric potential into the acceleration unit. The e-beam can be powered by a $\sim$ 10 A, 20 V dc unit.

The accleration unit can basically be two parallel conducting plates (with small holes to allow dusts to fly through) with relative dc bias 100-200 kV. The electric current between the two units due to the charged dust flux is minimal ($<$ 1mA). A dc power supply of 250 kV and 1 mA is adequate to power the acceleration unit. Separation between the two electrodes is large enough ($>$ 10 cm) to prevent arcing between the electrodes. The areas of the two electrodes are large enough (equal to or larger than the electrode spacing) so that the electric field is approximately parallel to the center axis and the electrode edge effect is reduced to minimum. The steering unit is two pairs of parallel electrodes that provide the dust beam direction control before entering the plasma.

The dust beam characterization unit is used to measure the hypervelocity dust beam properties, which include dust velocity, number of atoms per dust and dust mass. Dust velocity or kinetic energy can be measured by a combination of a retarding voltage and Faraday cup [17]. Another design based on dust stopping distance within silica aerogel can also be used. According to existing data, a 1-10 km/s hypervelocity dust can be stopped by aerogel, creating a carrot-track up to 200 times the size of the dust (up to 4 mm for dusts of 10 μm in radii). The dust remains intact when it slows down inside the aerogel [18], and its mass can be weighed afterwards using a microbalance.

B. HDBI for 2-D magnetic field mapping

As mentioned in the beginning, neutral atoms from HDBI can potentially be used for many diagnostics, including Zeeman splitting spectrocopy or CXRS. Here we only discuss the use of HDBI as a tool for two-dimensional mapping of the internal magnetic field of a-few-hundred-eV plasmas. Two-dimensional mapping of the magnetic field is presently impossible with known methods. Non-invasive, real-time measurement of magnetic field structures within high temperature plasmas, in particular, in spherical tokamaks, FRC's, RFP's, and spheromaks, when substantial deviation from vacuum field is expected, is long sought after. If it is successful, HDBI will have significant impact on our understanding of the dynamic process of magnetized plasma relaxation and self-organization. HDBI-induced optical emission (plume) is preferentially aligned along the magnetic field due to collisions with ions. The plume direction therefore measures the local magnetic field pitch angle [5], multiple (10-100) dusts together can produce a 2-D image of the magnetic field pitch angle distribution inside the plasma, in analogy with an actual solar system comet and the solar wind, simultaneously across the plasma. We estimate the photon signal related to each dust below.

To calculate photon emissivity due to the neutrals from HDBI, we use a simple model that assumes the number of visible photons emitted is proportional to its excitation cross section. Multiple photons can be emitted by each atom when the excitation cross section is greater than the ionization cross section. As pointed out by McNeill [19], this simplified model can underestimate the photon emissivity by orders of magnitude if local thermal equilibrium (LTE) can be reached at the dust surface. Since LTE is not proven for micron dusts, we adopt the simplified model, which gives the lower limit for photon emissivity. We have chosen LiI 670.8 nm and CI 477.2 nm as our preferred visible lines for the proposed diagnostics. According to standard collisional cross section data, 10 photons of LiI 670.8 nm per ionization is expected, and 0.01 photons per ionization for CI 477.2 nm. So LiI 670.8 nm photon flux can exceed CI 477.2 nm flux by several orders of magnitude for the same neutral density. The spread of the neutral is preferentially along the magnetic field line due to collision with ions. The visible plume spread along the magnetic field vs. perpendicular to the magnetic field is roughly proportional to the ratio of the plasma-ion thermal velocity to the dust velocity. The aspect ratio the plume is ~ 10 at a plasma temperature of 200 eV and dust velocity of 5 km/s.

Based on dust-penetration results, see Fig. 2, we have calculated total photon emission due to HDBI, see Fig. 4. The peak photon emission is 1.5×10^{12} LiI 670.8 photons located close to the $0.4a$. At each location within the plasma and along the dust path, the photons are emitted within the ionization time ~ 560 ns for LiI at 10^{13} cm^{-3} electron density. If the detector integration time is about the same, the equivalent dust-induced emissivity is 3×10^{19}ph/s. Since total number of photons is fixed, longer integration time decreases the signal-to-noise ratio (s/n). One μs or shorter time-integration is the best choice for HDBI, this is exactly opposite to NBI-based methods, when long integration time is used to increase s/n. The total useful photon signal is about 10^5 for LiI per dust within 1 μs of detection time, and the total optical efficiency is assumed to be 10^{-7} [9]. The noise level due to

Bremsstralung is orders of magnitude less if the detector integration time is 1 μs or less [20].

IV. SUMMARY AND CONCLUSIONS

Neutral atoms that exist within high temperature plasmas even for a short period (about the same as the ionization time) can be very useful for high temperature plasma diagnostics. We propose to use HDBI as an alternative neutral source to NBI and PI. HDBI appears to have many attractive features as a several-hundred-eV temperature plasma diagnostic according to our analysis. In particular, HDBI could be a simple, low cost approach to obtain internal magnetic field information in plasmas with magnetic field structures that are significantly different than vacuum fields, such as in spherical tokamaks, FRC's, RFP's, and spheromaks.

Electrostatic acceleration is appropriate to produce 1-10 km/s micron-size hypervelocity dusts. Model calculations confirmed deep penetration of these dusts into the center of several hundred eV, 10^{20} m^{-3} density plasmas. HDBI can be used for a wide range of high temperature laboratory plasmas. Using HDBI for 2-D magnetic field pitch angle measurement is discussed in details. Li dust-induced photon signals can be much greater than background noise. Micro-sec or less detection time works best for large s/n.

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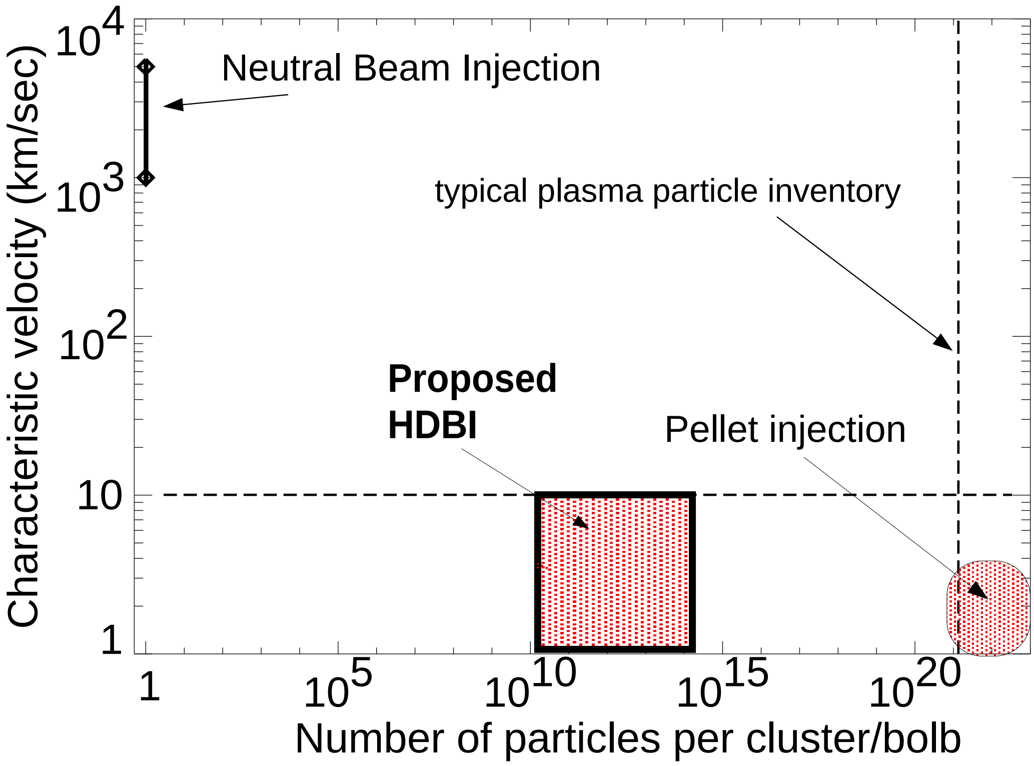

FIG. 1. Comparison of particle number and characteristic particle velocity for NBI, PI and the proposed HDBI. Typical plasma particle inventory is shown for comparison. HDBI is in a unique parameter space that can cause essentially no perturbation to plasma.

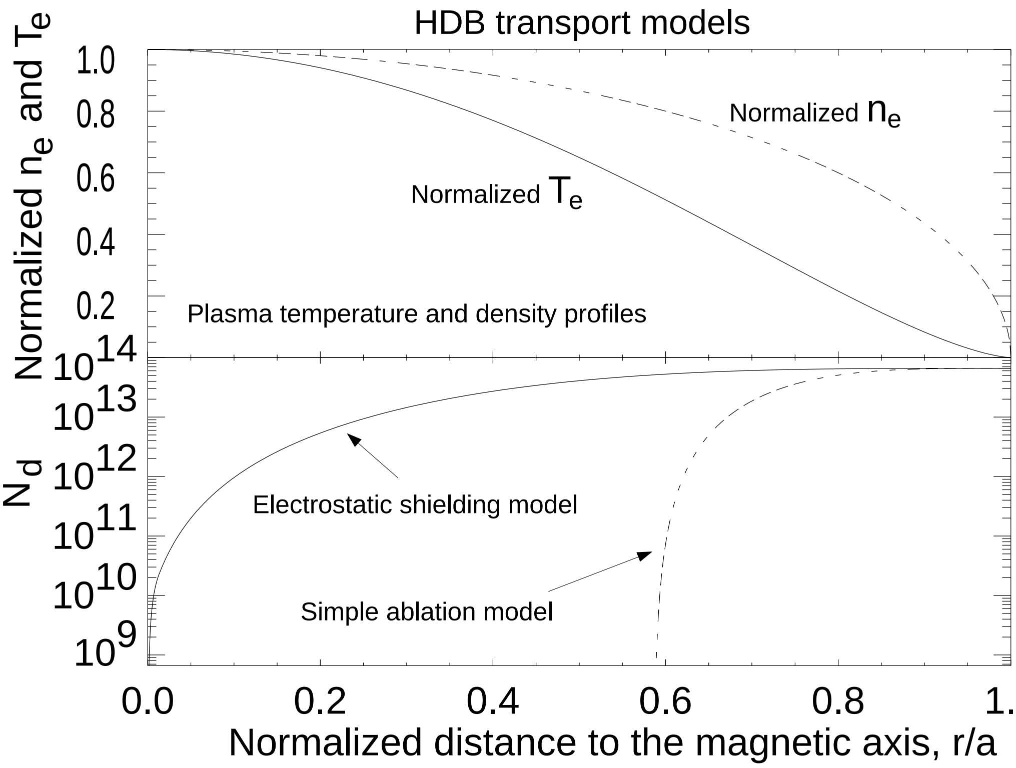

FIG. 2. Results for hypervelocity penetration into high temperature plasma with peak density 1.0×10^{20} m^{-3} and peak temperature 200 eV. The minor radius of the plasma is $a = 0.5$ m. Deep penetration of the dust into the high temperature is confirmed.

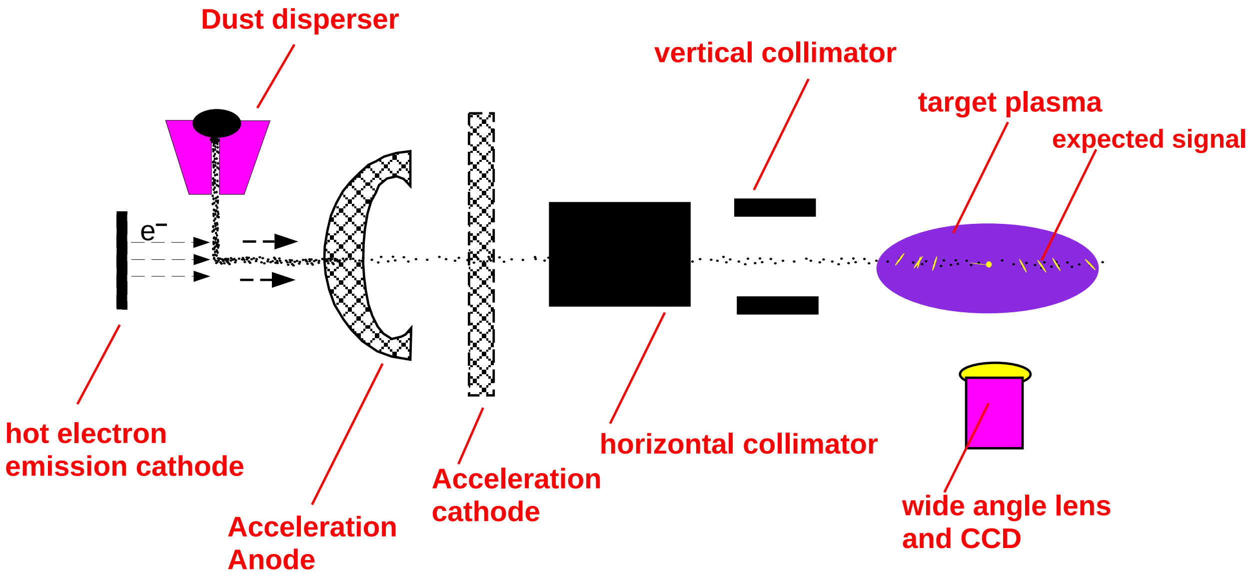

FIG. 3. Schematic design of a HDBI using electrostatic acceleration method. Key components of a HDBI include the dust disperser unit, the charging unit, the acceleration unit, the steering unit, and the diagnostic unit.

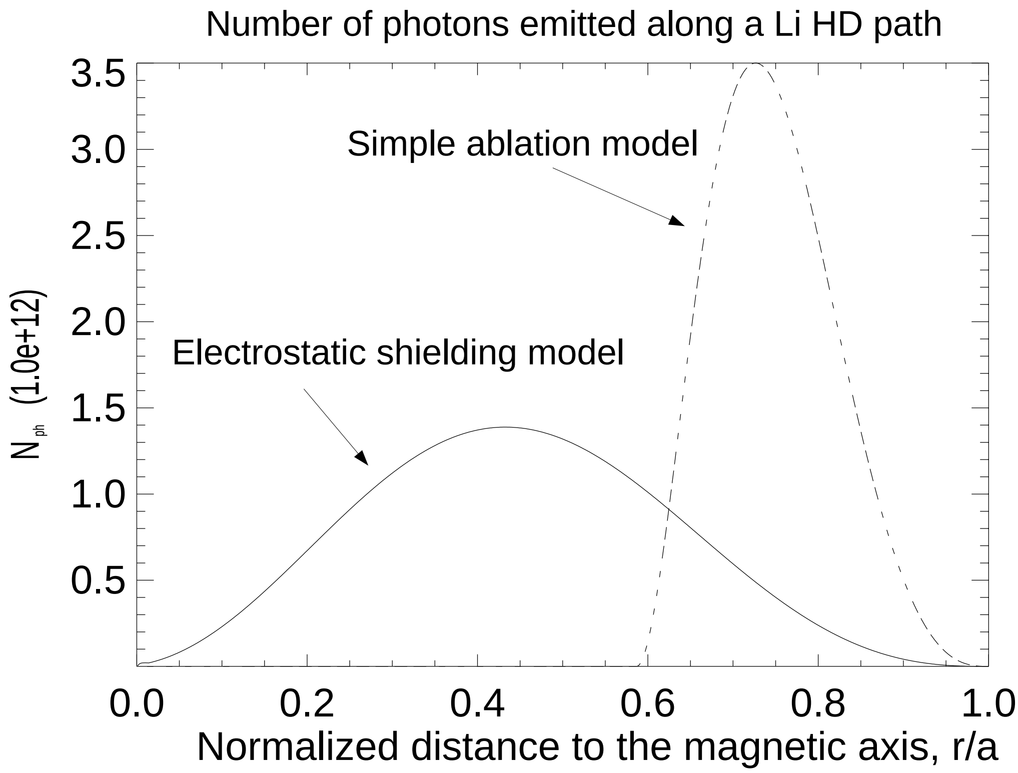

FIG. 4. Total emitted LiI 670.8-nm photons along the dust path for the same dust and plasma parameters as in Fig. 2.