Analytical and simulation studies for diode and triode ion beam extraction systems

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Abstract: This work is concerned with ion beam dynamics and compares the emittance to aberration ratios of two-and three-electrode extraction systems. The study is conducted with the aid of Version 7 of SIMION 3D ray-tracing software. The beam dependence on various parameters of the extraction systems is studied and the numerical results lead to qualitative conclusions.

Ion beam characteristics using diode and triode extraction systems are investigated with the aid of the computer code SIMION 3 D, Version 7.0. The diode (two electrode extraction system) and triode (three-electrode extraction, acceleration-deceleration system) extraction systems are designed and optimized with different geometric parameters of the electrode system, voltage applied to the extraction electrode, and plasma parameters inside the ion source chamber, as well as by the ion beam space charge. This work attempts to describe the importance of the acceleration-deceleration extraction system. It shows that besides an increase of the beam energy, the ion beam has lower emittance than the two-electrode extraction system. Ion beams of the highest quality are extracted whenever the half-angular divergence is minimum for which the perveance current intensity and the extraction gap have optimum value. Knowing the electron temperature of the plasma is necessary to determine plasma potential and the exact beam energy.

Key words: ion beam emittance, plasma meniscus, space charge, ion beam, SIMION computer program

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1 Introduction

Today, almost every ion source is studied by computer simulations before any part of its optical system is fabricated. Computer simulation codes provide a powerful tool for the optimization of charged particle systems [1]. However, the right program has to be selected to take full advantage of the computer. There are three classes of computer programs for the simulation of charged particle beams: (1) envelope models, where the beam is described by ellipses in different projections of phase space. These ellipses are transformed by a matrix (transfer matrix), for each optical element of the beam line. These kinds of programs can be used to analyze and optimize static beam transport sections (drift, electrostatic lenses, solenoids, and quadrupoles or sector magnets). (2) Particle tracking programs, which are more advanced than envelope models, can be used to transfer matrices by tracking single particles instead of three ellipse parameters. (3) Ray tracing programs are types of programs that can be used to simulate the charged particle beam within the extraction system.

An example of a ray trace computer program is SIMION [2]. Designing the extraction systems (diode or triode) generally has the aim of optimizing the optical properties and the current of the ion beam. The extraction of ions and the ion beam formation process seem to be the most crucial points in ion implantation, electromagnetic separation and plasma diagnostics [3]. Optimization of the beam optics should result in a significant improvement in the emittance of the source [4].

The ion beam extraction from any ion source is affected by many parameters such as geometry, kinds

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of electrodes and applied potentials, the space charge of the extracted beam and the shape of the plasma boundary. The plasma boundary itself is dependent on the plasma density, the extraction field strength and the electron distribution of the slow electrons [5–7]. In the work leading up to that described here, the diode (two-electrode extraction system) and triode extraction system (three-electrode systems) are designed and optimized with many various parameters using the SIMION computer program.

2 Simulation process for the diode and triode extraction systems

The second important step for plasma ion sources after the production of suitable plasma is to extract the plasma ions in the form of an ion beam with a given kinetic energy.

This can be done by using an electrode system that is biased at a negative voltage with respect to the plasma. The value of the extracted ion current should be large, its divergence low and the ion losses to the extractor electrode must be small. Ion beam extraction from any kind of ion source is influenced by many parameters such as geometry, applied extraction voltage, space charge in the extracted beam and finally the shape of the plasma boundary. Diode and triode extraction systems are designed and simulated with different parameters using the SIMION computer program, Version 7 [2].

The triode extraction system provides a negative potential with respect to the plasma on the axis of the extraction system. A negative potential between the acceleration and the deceleration electrode creates a barrier for electrons for the extracted beam region to keep them inside the ion beam. These electrons are necessary for space-charge compensation. The triode extraction system consists of three electrodes, a plasma electrode, an acceleration electrode and a deceleration electrode. The plasma electrode terminates the plasma surface at the boundary of the discharge. The downstream side of this electrode must be designed to work as a focussing electrode to provide the proper electric field configuration for optimal ion trajectories.

SIMION [8] provides direct and highly interactive methods for simulating a wide variety of general ion optics problems, such as designing and analyzing charged particle (ions and electrons) lenses, ion transport systems, various types of mass spectrometers, detector optics, time-of-flight instruments, ion traps, quadrupoles, magnetic sectors, etc. Ion trajectories can be simulated and flying ions singly or in groups through the created geometry displayed as lines and automatically re-flown.

2.1 Significance of plasma potential at low energies

An acceleration-deceleration beam extraction system has been used, as shown in Fig. 1. The beam is accelerated with a much higher voltage V_{ex} and then is retarded to its final energy with the use of decelerating voltage V_{deo}. The acceleration-deceleration system [9] is applied to avoid compensating electrons being accelerated back into the source, thus destroying its rear side and leaving the ion beam uncompensated. Also the accelerating-decelerating system will yield beam trajectories closer [1] to the axis and thereby with less spherical aberration. Considering the space-charge effect, the Child-Langmuir law expresses the extraction ion current density as:

$$J_{\mathrm{i}} = \frac{4}{9}\varepsilon_{\mathrm{o}}\left(\frac{2e}{M}\right)^{1/2}\frac{V_{\mathrm{o}}^{3/2}}{a^2}, \tag{1}$$

where V_{o} is the potential difference between the source and the extraction electrode, a is the distance from the plasma boundary to the extraction electrode, and ε_{o} is the dielectric constant of the vacuum. Also, V_{O} is expressed as the summation of the plasma floating potential V_{P} and V_{ex} the potential difference between the cathode and the extraction electrode.

$$V_{\mathrm{O}} = V_{\mathrm{P}} + V_{\mathrm{ex}}. \tag{2}$$

Also the extraction ion current density J_{i} is expressed by the electron temperature T_{e}, ion mass M and electron density n_{e}, as:

$$J_{\mathrm{i}} = en_{\mathrm{e}}\left(\frac{kT_{\mathrm{e}}}{M}\right)^{1/2}\exp\left(-\frac{1}{2}\right), \tag{3}$$

where k is Boltzmann's constant and e the absolute value of the electron charge. The electron current density J_{e} is dependent on the plasma potential V_{P} as:

$$J_{\mathrm{e}} = -en_{\mathrm{e}}\left(\frac{kT_{\mathrm{e}}}{2\pi m}\right)^{1/2}\exp\left(\frac{-eV_{\mathrm{P}}}{kT_{\mathrm{e}}}\right), \tag{4}$$

where m is the electron mass. Since $J_{\mathrm{i}} + J_{\mathrm{e}}$ equals zero in a state of equilibrium, then we obtain:

$$\frac{1}{M^{1/2}}\exp\left(-\frac{1}{2}\right) = \frac{1}{(2\pi m)^{1/2}}\exp\left(\frac{-eV_{\mathrm{P}}}{kT_{\mathrm{e}}}\right), \tag{5}$$

$$\therefore V_{\mathrm{P}} = \frac{kT_{\mathrm{e}}}{2e}\ln\left(\frac{A}{1.26\times10^{-3}}\right). \tag{6}$$

where A is the ion mass number.

As a result, one can conclude that the plasma floating potential V_{P} is proportional to the electron temperature T_e. By taking plasma temperature kT_e equals 10 eV for the Argon gas (A=40). From Eq. (6) the plasma floating potential V_P will be 51.8 V. Therefore if the cathode potential is 100 V and the target is grounded, the exact beam energy bombarding the target is 100+51.8=151.8 V.

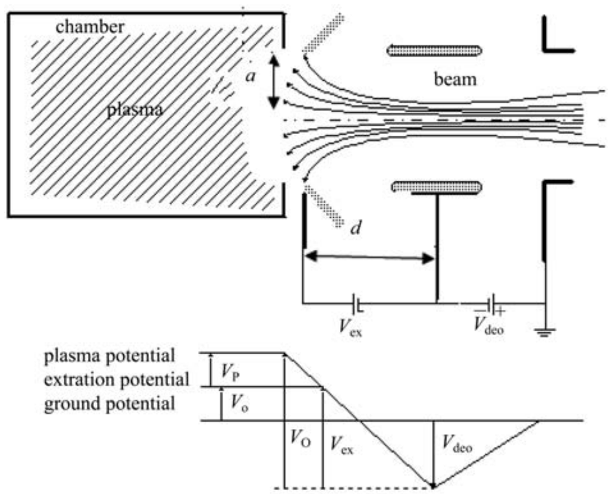

Fig. 1. The acceleration-deceleration extraction system, and the potential distribution.

2.2 Beam perveance

The space-charge effect in beams is conveniently characterized by the perveance taking into account the magnitudes of the beam current and the accelerating voltage. Beam perveance has been studied and calculated in order to define the beam trajectory and beam boundaries. In the present work beam perveance is introduced in order to differentiate between the perveance of different beam particles and gases. Charged ion beams are usually drawn from a space-charge ion source at zero initial velocity. The maximum beam current occurs when the electric field becomes zero at the plasma emitter surface. Let s be the distance between the two parallel plates with s=0 at the emitter and $s=d$ at the anode.

The Poisson equation becomes:

$$\frac{\mathrm{d}^2V}{\mathrm{d}s^2}=-\frac{\rho}{\varepsilon_o}, \tag{7}$$

where V is the electric potential, ρ is the ion density and ε_o is the permittivity. But the ion beam intensity $J=\rho\nu$, $\nu=\sqrt{\frac{2\mathrm{eV}}{m}}$, e, m, ν are the charge, the mass and the velocity of the ion. Substituting in Eq. (7), the Poisson equation becomes:

$$\frac{\mathrm{d}^2V}{\mathrm{d}s^2}=\frac{J}{\varepsilon_o}\left(\frac{m}{2e}\right)^{1/2}V^{-1/2}, \tag{8}$$

but the maximum space charge is achieved when $V=0$ and $\frac{\mathrm{d}V}{\mathrm{d}s}=0$ at s=0. Then the maximum current density becomes:

$$J=P\frac{V_o^{3/2}}{a^2}, \tag{9}$$

where V_o is the effective extraction voltage, and P is the perveance of the ion beam given by

$$P=\frac{4\varepsilon_o}{9}\left(\frac{2e}{m}\right)^{1/2}. \tag{10}$$

Eq. (9) is a relation between the charge current J and $V^{3/2}$, which is called the Child-Langmuir equation.

Killer and others [10, 11] found that the actual transport ion current is given by

$$I_{tr}=P\frac{S^2}{1+aS^2}V^{3/2}, \tag{11}$$

where a = aberration factor, S is the aspect ratio.

From the above equation, one can conclude that the maximum normalized current can be obtained from the following equation

$$I_{tr.n}=7.03\times10^{-4}V^{3/2}\frac{S^2}{1+aS^2}\quad(\mathrm{A/kV^{3/2}}). \tag{12}$$

The following table gives the calculated space-charge perveance for electron, proton, deuteron, He^+, N^+ and Ar^+ ion sources. The microperveance is defined as:

$$1\ \mu\mathrm{P}=1\times10^{-6}\ \mathrm{A/V^{3/2}}.$$

Figure 2 shows the relation between the calculated space-charge perveance for proton, deuteron, He^+, N^+ and Ar^+ ions with the mass number. It shows the decrease of the beam perveance with the increase of the mass number of the ion species.

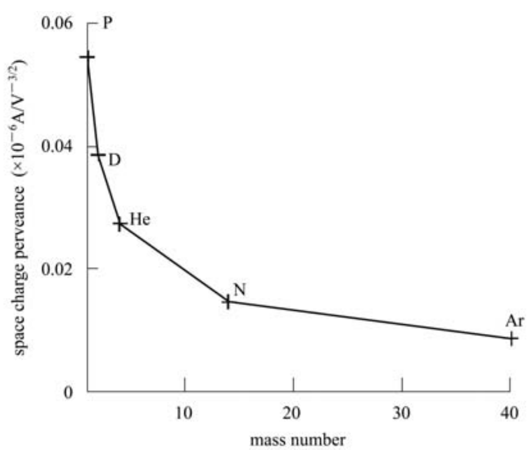

Fig. 2. Variation of the beam perveance with the atomic number of the ion species.

Table 1. Variation of ion beam perveance p (μP) with the atomic mass m.

	e	p	D^+	He^+	N^+	Ar^+
p/μP	2.334	0.0545	0.0385	0.0272	0.0146	0.00861

3 Influence of the beam aberration on the beam extraction equation of the Child-Langumier law

For a more refined two-gap extraction system, a=1.7, a=3, using these values one can conclude at once that the maximum normalized current to be obtained from one round aperture is obtained by the following equation:

$$I_{\rm tr}=7.03\times10^{-4}V^{3/2}\left(\frac{S^2}{1+aS^2}\right). \tag{13}$$

Figure 3 shows the relation between the ion beam current calculated by Child's equation (I-Child) and the transported current (I- transport) considering the influence of the aberration factor with the aspect ratio.

Figure 4 shows the relation between the extraction voltage and the transported ion current for a proton P^+, deuteron D^+, helium ion He^+, nitrogen ion N^+, and an argon ion Ar^+. This curve shows that the current increases with the extraction voltage but decreases with increasing the mass number.

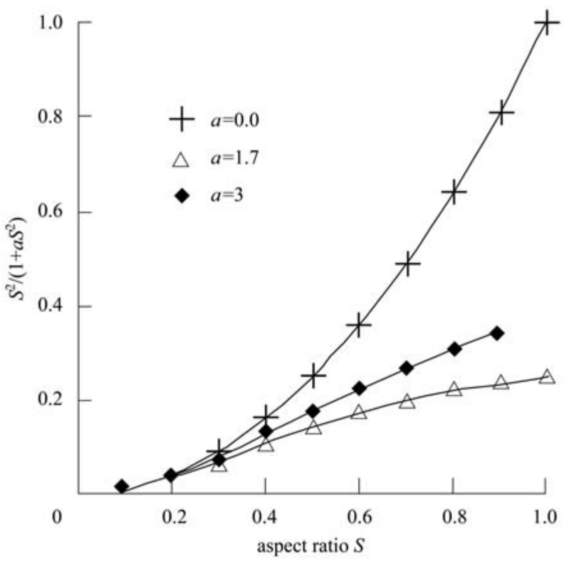

Fig. 3. General shape of the actual extracted current considering the influence of aberration factor with the aspect ratio.

The basic for the present analytical treatments of the beam optical properties of the extraction systems was yielded by Harrison [12] who investigated the profile of beams in the extraction gap. He proposed that the experimental data be consistent with the concept that the ions were emitted from curved surface, whose curvature was determined by self-consistent space-charge limited flow of ions. By analogy with the problems of electron flow from curved cathodes discussed by Pierce [13], the result is derived as:

$$\frac{I}{V^{3/2}}=\frac{8\pi\varepsilon_0}{9}\left(\frac{Z_{\rm e}}{AM_{\rm P}}\right)^{3/2}\frac{1-\cos\theta}{(-\alpha)^2}. \tag{14}$$

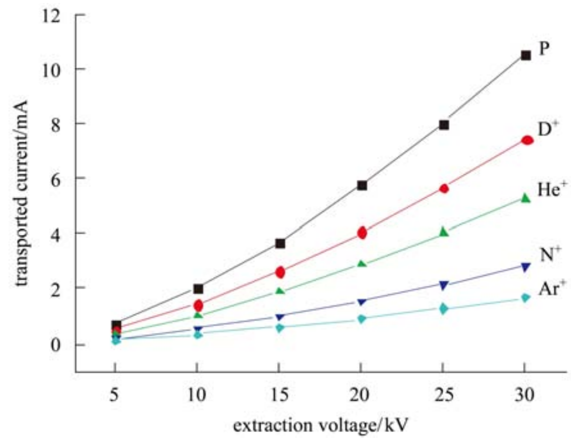

Fig. 4. (color online) Variation of the transported current with the extraction voltage at aberration factor a=1.7.

4 Minimum half-angular divergence

The ion beam of converging angle θ arrives on the other side of the aperture in the second electrode with a final angular divergence ω, after being transmitted through the aperture of the extraction electrode (Fig. 5). The aperture effect is illustrated by changing the half-angular divergence of the beam ψ, so that the final half angular divergence is $\omega=\theta-\psi$.

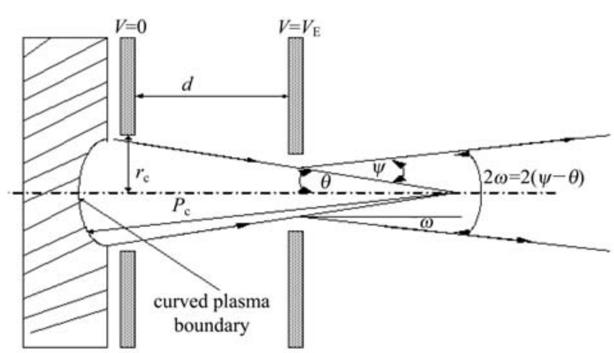

Fig. 5. The extraction system.

The semi angle of divergence in the lens $\psi=a/3d$ (for circular aperture)

$$\psi\ =\ (a/d-\theta)/3, \tag{15}$$

$$\omega\ =\ \theta-\psi=(1-1.67P/P_{\rm c})a/d, \tag{16}$$

Using the expansion of Eq. (10), valid to the first order in a/d, one obtains the result

$$\theta = (0.625a/d)(1 - P/P_c). \tag{17}$$

C. Optimum perveance

From Eq. (10), it is evident that ω versus P should reach a minimum whenever the perveance P_c has the optimum value

$$P_{op} = P_c/1.67 = 0.6P_c. \tag{18}$$

5 Extraction system

Figure 6 shows that the extraction system may be *a* two-electrodes system (diode system in Fig. 6(a)) or *a* three-electrodes system (triode system in Fig. 6(b)). To optimize both the beam diameter and the beam emittance for the diode and triode systems, the structure of the electrodes has been determined with the aid of the SIMION computer code.

Figure 7 is the relation between the beam diameter and the anode voltage measured 10 cm from the second electrode using the SIMION simulation computer code. It shows that the beam diameter decreases with increasing the anode voltage for both the diode and the triode systems.

Figure 8 describes the relation between the beam emittance and the extraction voltage measured at 10 cm from the second electrode for both the diode and triode using SIMION simulation computer code. It shows that the emittance for a triode system increases with increasing the extraction voltages, while the emittance decreases with increasing the extraction voltage for the diode system. It is obvious that the triode system has a better influence on the beam optics for the same operating condition. The triode system has minimum beam diameter and minimum beam emittance. For the three electrodes (acceleration-deceleration) system, in addition to increasing the beam energy, it also enhances the beam optics.

Figure 9 gives the theoretical prediction for variation of the angular divergence of the beam with the beam perveance ratio (P/P_c) at different values of a/d.

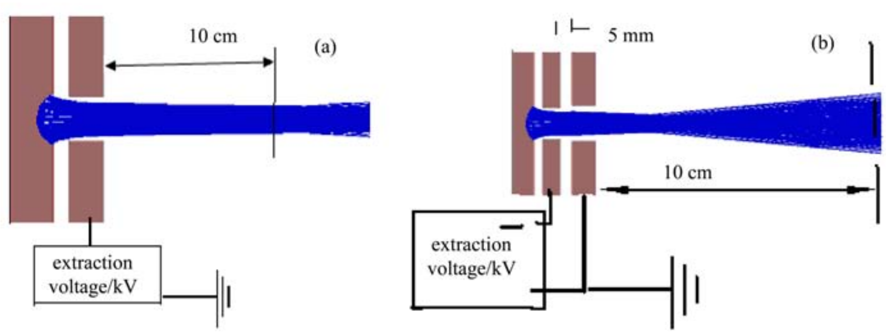

Fig. 6. Simulation of the (a) diode and (b) triode extraction systems.

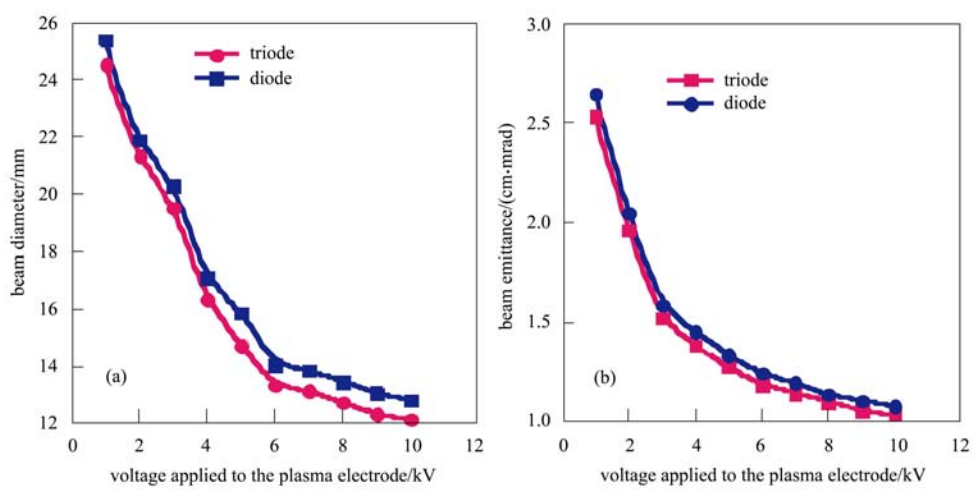

Fig. 7. Relation between the beam diameter and the plasma voltage for both the diode and the triode extraction systems.

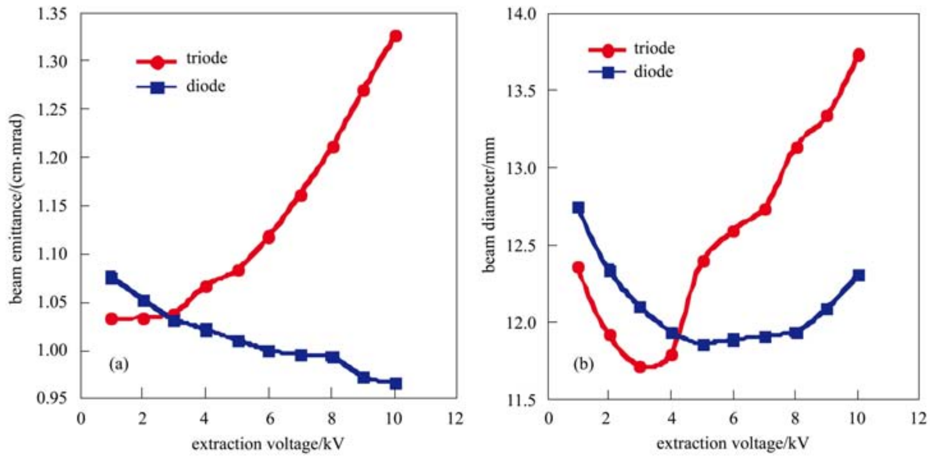

Fig. 8. Relation between the extraction voltage and beam emittance for both the diode and the triode extraction systems.

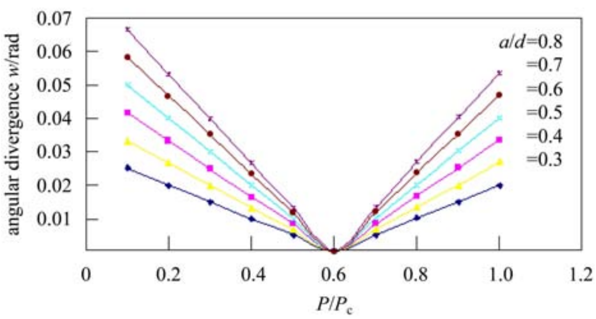

Fig. 9. (color online) The angular divergence of the beam perveance at different ratios of a/d.

The similarity is obviously clear and the minimum beam divergence occurs at the optimum perveance. Also, the optimum condition for the triode system appears at lower extraction voltage than the diode system. This means that the triode system is useful more than the diode system for the extraction of the ion beam.

6 Conclusion

This work is concerned with ion beam dynamics and compares the emittance-to-aberration ratios of two- and three-electrode extraction systems. The study is conducted with the aid of Version 7 of SIMION 3D ray-tracing sofwtare. The beam dependence on various parameters of the extraction systems is studied and the numerical results lead to qualitative conclusions.

From this study, it is concluded that:

1) The extraction current increases with the extraction voltage but the beam perveance decreases with increasing the atomic number.

2) A high perveance ion beam requires a high ratio of a/d, but at the same time this causes an increase of the angular divergence of the beam. So careful design is needed to choose the optimum value of a/d with shaping the extraction electrode to prevent aberration in ion beams.

3) An acceleration-deceleration system (triode) is found to yield lower beam emittance than the diode extraction type and this is due to its effect on beam space-charge compensation.

Both analysis and the SIMION code deduce the minimum beam emittance at an optimum beam perveance.

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