Ion Sources

Spring, 2021

Kyoung-Jae Chung

Department of Nuclear Engineering

Seoul National University

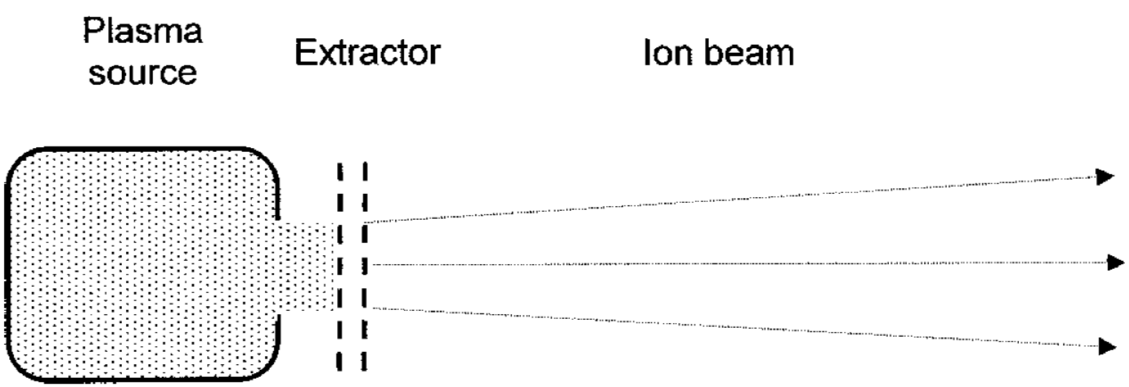
Ion source, plasma source, and plasma gun

- Most, but not all, ion sources are plasma-based in the sense that they contain a plasma as an essential part; the plasma source, which constitutes an important part of the ion source, is used to produce ions that are then formed into a more-or-less energetic ion beam.
- Plasma source: In general, we might say that the ions formed by a plasma source usually possess little directed energy – the ion drift energy is zero or at least small compared to the mean thermal ion energy.
- Ion source: The ions formed by an ion source usually possess significant directed energy – the ions are in the form of a beam and have a drift energy that is large compared to the mean thermal energy.

- Plasma gun: Consider the case of a plasma that is formed in such a way as to possess substantial drift, perhaps by making use of the Hall effect (i.e., the jxB force) to accelerate the plasma as a whole at the same time as it is formed. We can view this either as a plasma with high drift velocity, or as a relatively low energy ion beam embedded in its own background sea of cold electrons. A device that produces a streaming plasma of this general kind is often called a plasma gun.

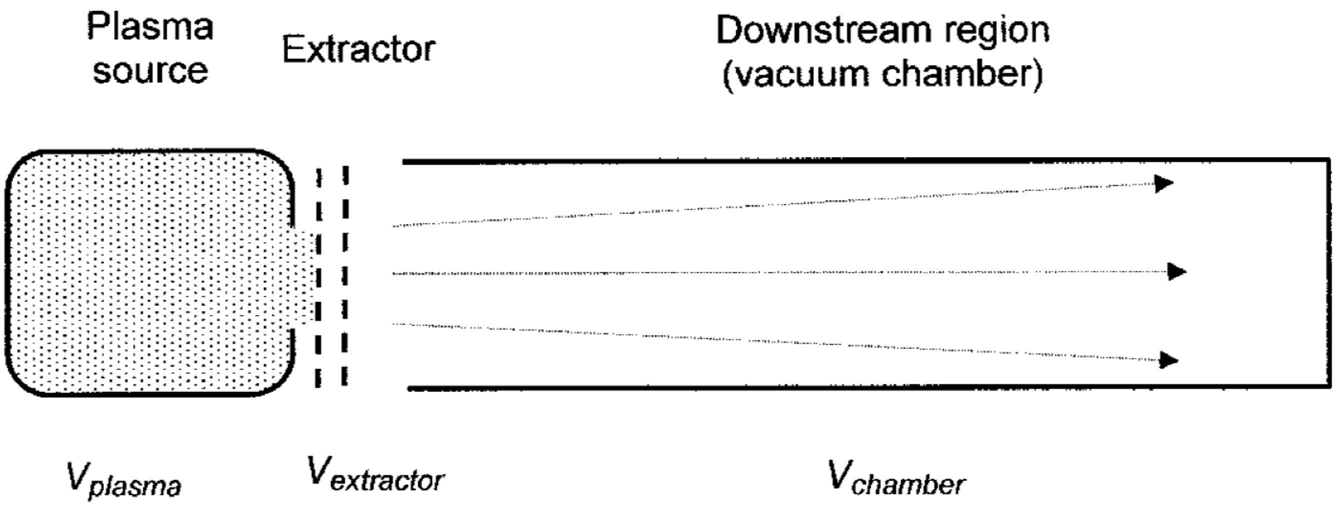
The ion source consists of a plasma source and an extractor

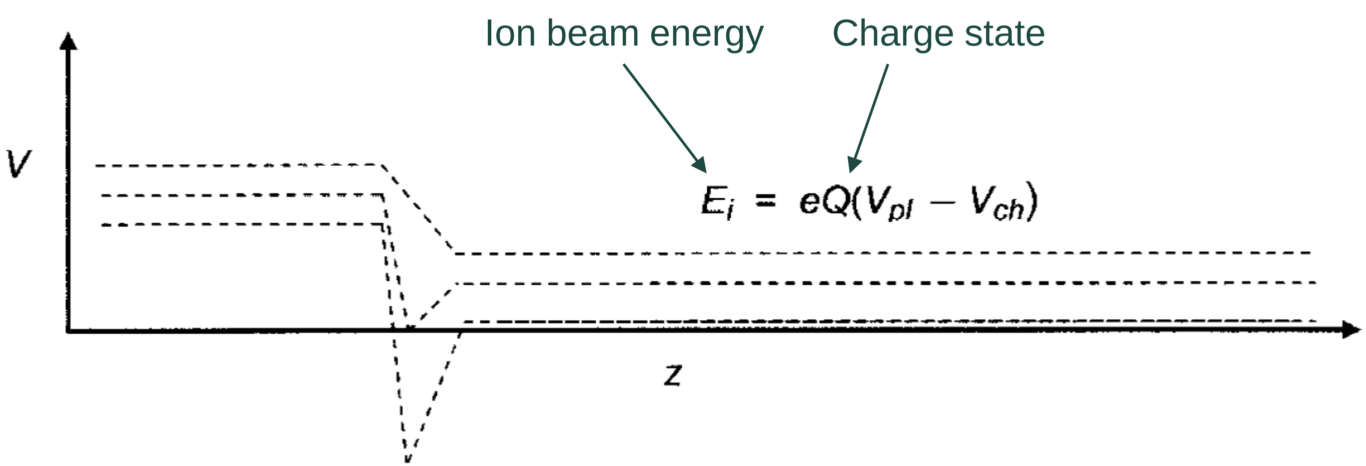
- Plasma source: The ion source contains a plasma source as its most essential component. Plasma is formed within the heart of the ion source, and the hardware and electronics needed to form the plasma are some of the key parts of the overall ion source setup. The properties and features of the plasma determine to a large extent the kind of ion beam that is produced.
- Extractor: The ion beam is formed from the plasma by an electrode system – specially shaped metal electrodes to which voltages are applied. This beam-forming electrode system is commonly called the extractor, and the grids are sometimes called the extraction electrodes, implying that ions are extracted from the plasma by the electrodes.



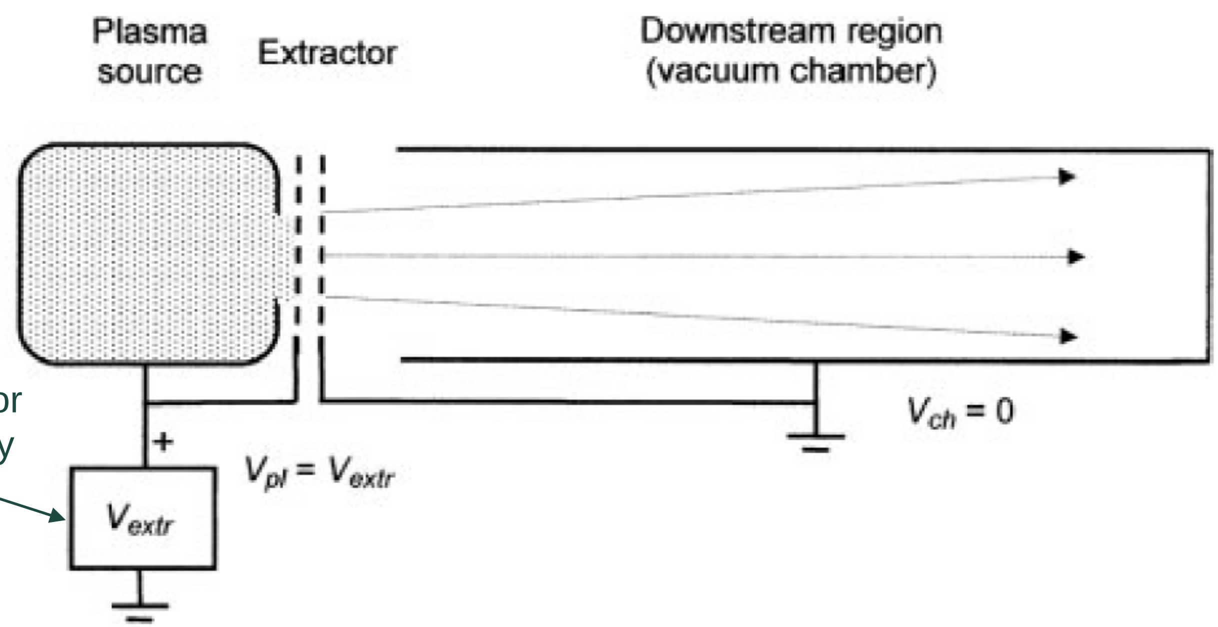
The elemental ion source: a plasma source for ion production and an electrode system for forming the ions into a beam.

Potential distribution of ion source



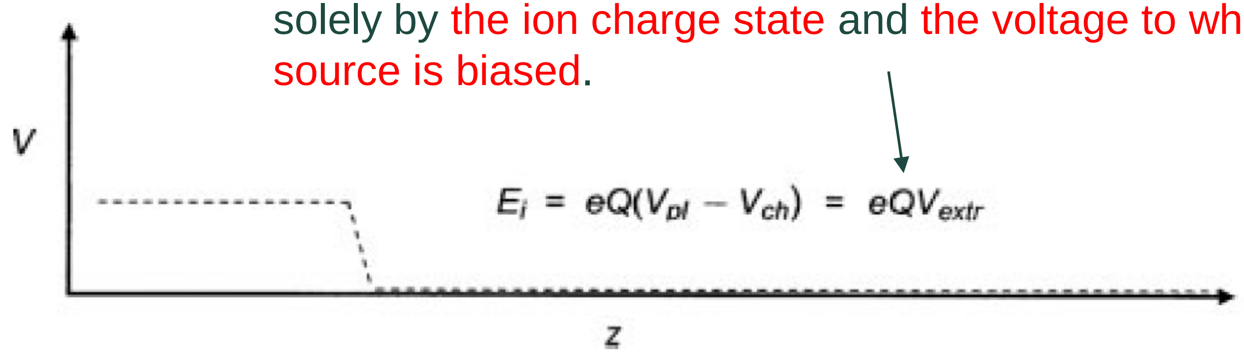


Typically, the vacuum chamber is grounded and the plasma source is positively biased



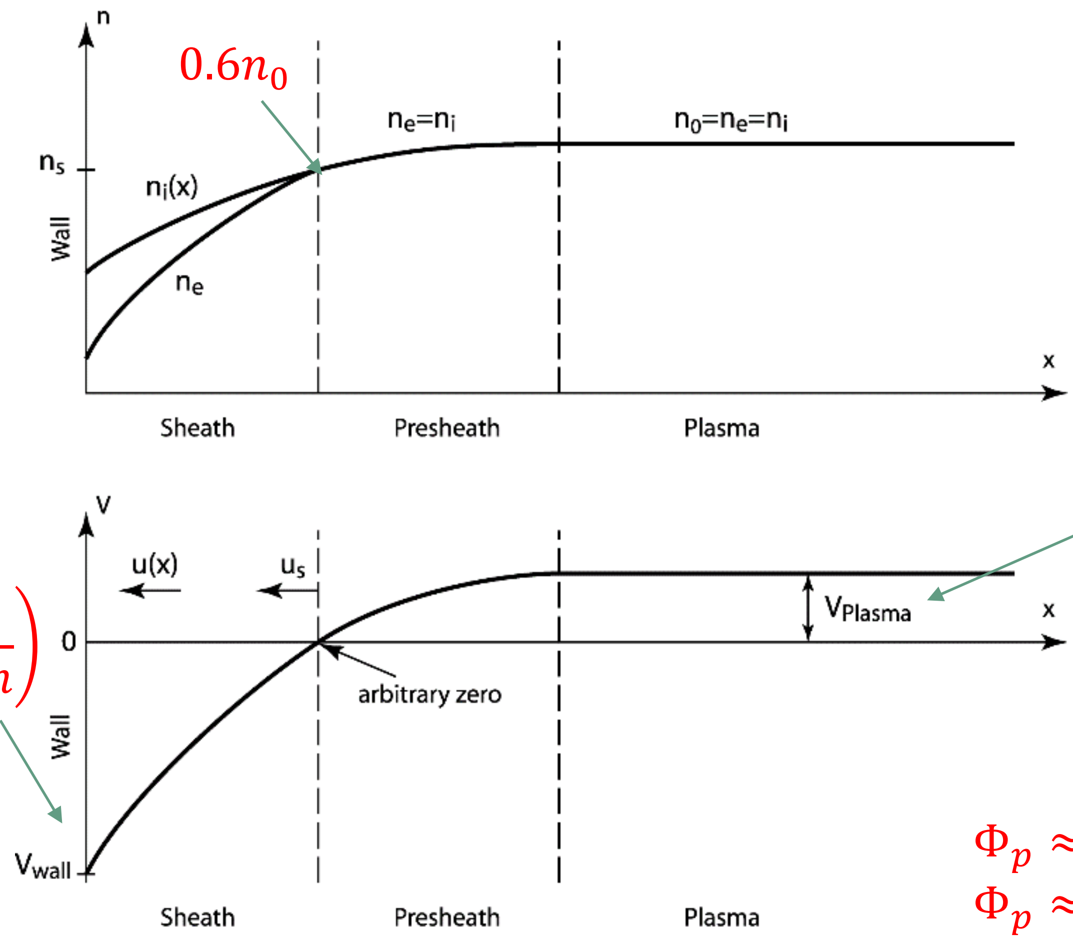
Extractor supply or accelerator supply

The ion beam energy (energy of the ions in the beam) is determined solely by the ion charge state and the voltage to which the plasma source is biased.



More accurately, the plasma potential needs to be considered

- The plasma potential (defined as the potential of the plasma with respect to the wall of the chamber that contains it) is usually of the order of $3\mathrm{T_e}$, and the electron temperature $\mathrm{T_e}$ is often only a few eV.



$$\frac{\mathrm{T_e}}{2}$$

$$\Phi_w = -\frac{\mathrm{T_e}}{2}\ln\left(\frac{M}{2\pi m}\right)$$

$\Phi_w \approx -2.8\mathrm{T_e}$ for H

$\Phi_w \approx -4.7\mathrm{T_e}$ for Ar

$\Phi_p \approx -3.3\mathrm{T_e}$ for H

$\Phi_p \approx -5.2\mathrm{T_e}$ for Ar

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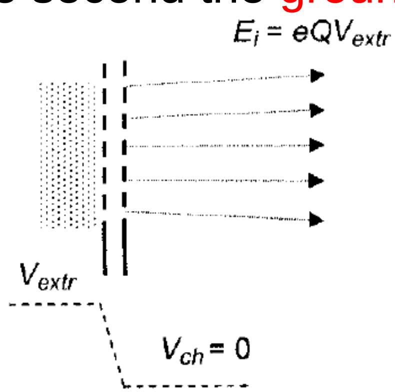
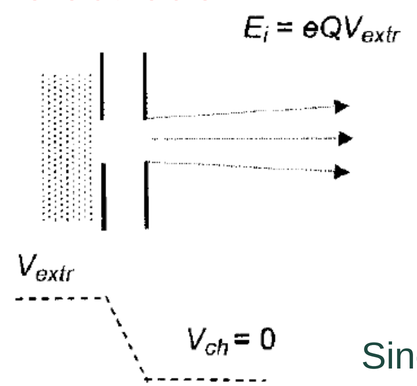
Ion beam formation

- The extractor geometry is mainly determined by the size and shape of the wanted beam. If we wish to form a small diameter beam of circular cross section, then the extractor should contain just one small hole; we call this a single aperture design. If a broad beam is needed, then the extractor should be comprised of an array of many apertures – a multi-aperture extractor. Each aperture might be a small circular hole or there may be many slit apertures making use of rail electrodes.
- In the simplest case, two separate electrodes (or grids) are used. The first electrode is in contact with the plasma and is maintained at the positive high voltage that is the extraction potential, and the second electrode is fixed at ground potential. Thus the ion-accelerating electric field is located between the electrodes of the extractor. The first electrode is often called the plasma electrode and the second the ground electrode.



Multi-aperture



Single aperture

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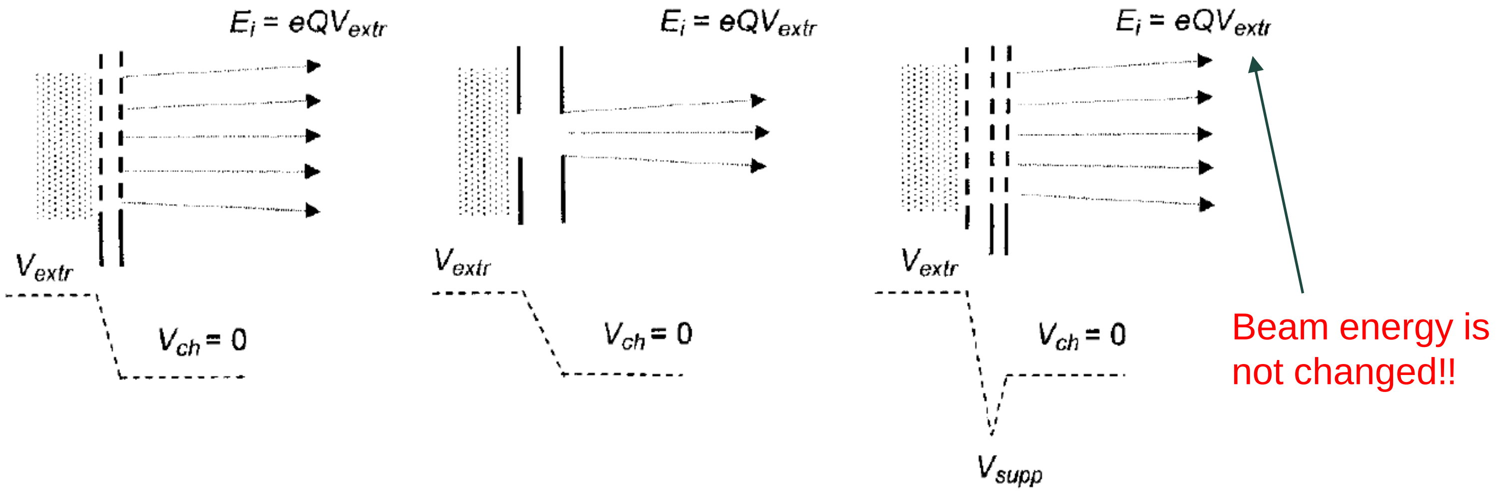
Ion beam formation

- Often a three-electrode extractor design is used, with the new electrode inserted between the plasma grid and the ground grid and biased to a relatively low negative voltage. The function of the middle grid is to inhibit the backflow of electrons into the ion source from the downstream region, and so it is often called the suppressor grid.
- This three-grid configuration is also called an accel-decel extractor system, because ions are accelerated in the first gap and decelerated in the second gap.
- When the extraction voltage is very high, then additional electrodes are often used whose purpose is primarily to provide a defined grading of the very high electric field so as to be able to hold off the high voltage without breakdown.



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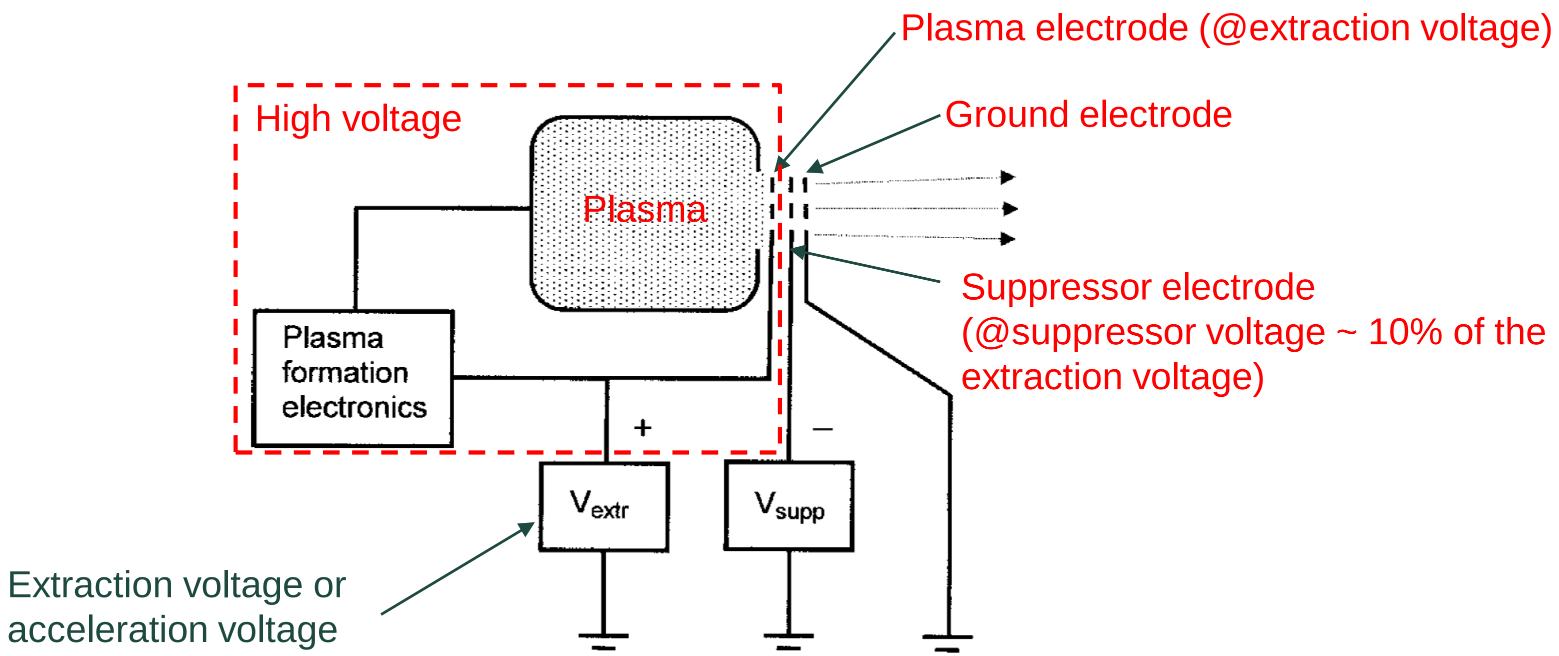
Elemental ion source showing all essential component parts

- We use a high voltage power supply to bias the plasma to high positive voltage, and to set the extraction voltage; this power supply is often called the extractor power supply, and its voltage is the extraction voltage or the acceleration voltage. This is the voltage that determines the ion energy.
- Plasma formation requires its own power supplies and electronics systems, and this entire electrical package must be biased at the extraction voltage, since the plasma and plasma containment device are also at extraction voltage. This makes the ion source complicated.



Ion beam parameters

- [Ion beam species] The ions might be gaseous or metallic (formed from a gas or from a metal, e.g., He^+ or Ti^+), atomic or molecular (ionized atoms or ionized molecules, e.g., N^+ or N_2^+), singly, doubly or multiply ionized (e.g., Ar^+, Ar^{2+} or Ar^{n+}), or as is very often the case, a mixture. These parameters are determined by the plasma source. An important part of understanding the overall ion source is the physics of the plasma formation and plasma confinement system.
- [Operation mode] The ion beam might be operated in a DC mode (CW mode) or in a repetitively-pulsed mode. If pulsed, the pulse length might be as long as hundreds of milliseconds or as short as nanoseconds. Beam pulsing can be achieved either by pulsing the plasma source or by gating the beam electrically (or magnetically, or even mechanically).
  - Operating the plasma source in a repetitively pulsed mode has the advantage that the mean power levels are lower. Then the electrical systems can be smaller, and concerns such as floating of power supplies to extraction voltage and source heat removal are reduced by a factor equal to the reciprocal of the duty cycle.
  - Plasma rise and decay times are often of the order of microseconds to hundreds of microseconds or more, so that for sub-microsecond beams it is in general necessary for the beam to be gated rather than the plasma, for example by using a pulsed extractor configuration.

Ion beam parameters

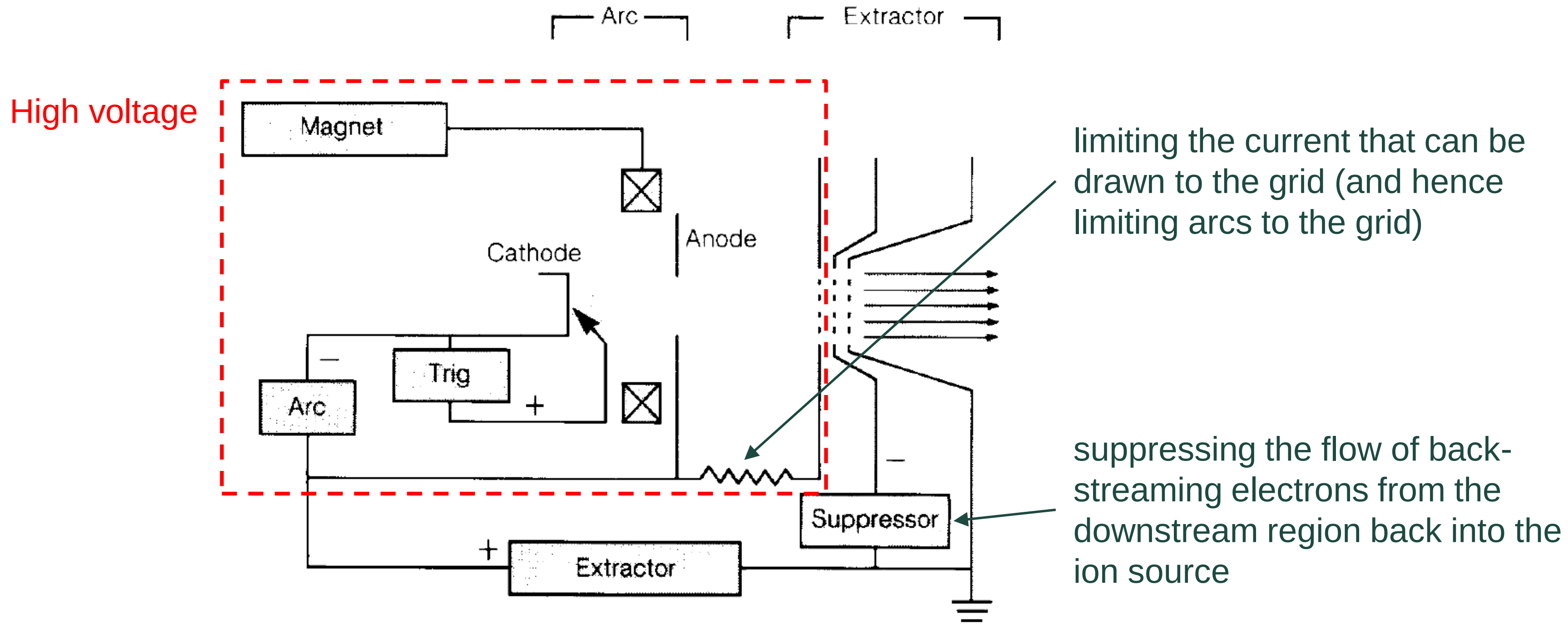
- [Beam energy] The term beam energy refers to the energy per ion in the beam, as the product of the ion charge and the extraction voltage. In a high vacuum ambient the ions propagate with no significant loss of energy by collisions with the background gas. But for higher vacuum system gas pressures, perhaps starting in the 10^{-4}–10^{-6} Torr range depending on the particular beam ions and beam setup, collisions with background gas neutrals can lead to reduced beam energy as well as other effects.
- [Beam current] The beam current is the total current carried by the ions in the beam. The measurement of ion beam current is affected by the followings:
  - [Background neutrals] Collisions with neutral atoms in the gas ambient can be charge-exchange collisions, in which the electron of a cold atom is transferred to a fast ion, leaving a fast neutral and cold ion. In this case a measurement of the beam current based on calorimetric measurement will include the neutral atom flux.
  - [Background electrons] Electrons are formed by ion-neutral collisions in the background gas, and secondary electrons are formed by ion collisions with the metal electrodes of parts of the extractor and by ion collisions with the beam target. The space-charge-neutralizing feature of the background electrons is a desirable feature, because it prevents the ion beam from 'space-charge blow up'. However, the cold electrons formed as secondaries from the ion beam target make problematic the measurement of beam current via the current to a biased collector plate.

Ion beam parameters

- [Electrical current vs particle current] We can denote the electrical current of a beam of multiply charged ions by the symbol I_{elec} and the particle current by I_{part}. For ions of charge state Q+, they are related by $I_{elec} = Q \times I_{part}$ and thus for highly stripped ions the electrical current can be much greater than the particle current.
  - The units emA and pmA for electrical milliamperes and particle milliamperes, and eμA and pμA for electrical microamperes and particle microamperes, have come into use.
  - When the beam contains a distribution of ion charge states, the situation is yet further complicated in that the mean charge state when expressed as the mean of the electrical current fractions can be different from the mean charge state expressed in terms of the particle current fractions.
- [Other beam parameters including beam shape and size]
  - A narrow beam or a broad beam, determined by the extractor geometry.
  - The beam divergence and the related parameters emittance and brightness relate to the angular characteristics of the beam.
  - The ion beam energy spread is sometimes of importance; by this we refer to the spread in beam ion energy that is introduced by the thermal energy of the ions in the plasma (ion temperature) prior to extraction, by any variation in plasma potential in the pre-extraction plasma that affects the extracted ion energy, and any other energy spread effects introduced by the extractor or the downstream environment.

An example: vacuum arc ion source

- The plasma is formed at high voltage, and it is this voltage that determines the ion energy. All of the plasma formation equipment, including the arc power supply, are biased to extractor potential.
- Ions are created within the plasma, and they undergo a potential drop equal to the extractor voltage.
- The suppressor grid serves its electron-blocking purpose, and its voltage is unrelated to the ion energy.



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Introduction to ion beam extraction

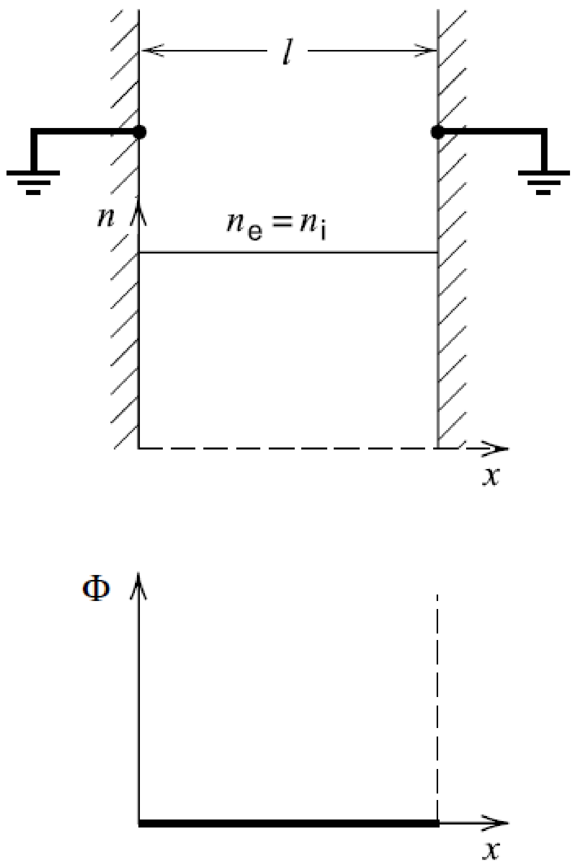
- In general, an ion source consists of two parts. The first is the plasma generator that provides ion production and thus serves as an ion reservoir. The second is the extraction system for accepting ions from the reservoir and forming an ion beam.
- Both parts of the source may be treated independently as long as the plasma generator provides ions at the required current density and covers the whole area of the extraction system.
- The extraction system determines the beam properties such as ion current and beam quality in general. The extraction system thus fulfils the task of adapting the plasma generator to the beam transport system that follows.
- Discussion is restricted to the case of extraction systems with circular aperture, for extraction of positively charged ions, and without magnetic field in the vicinity of the extractor. Although extraction systems are treated in general, most examples are focused on high current, high brightness ion sources for particle accelerators.

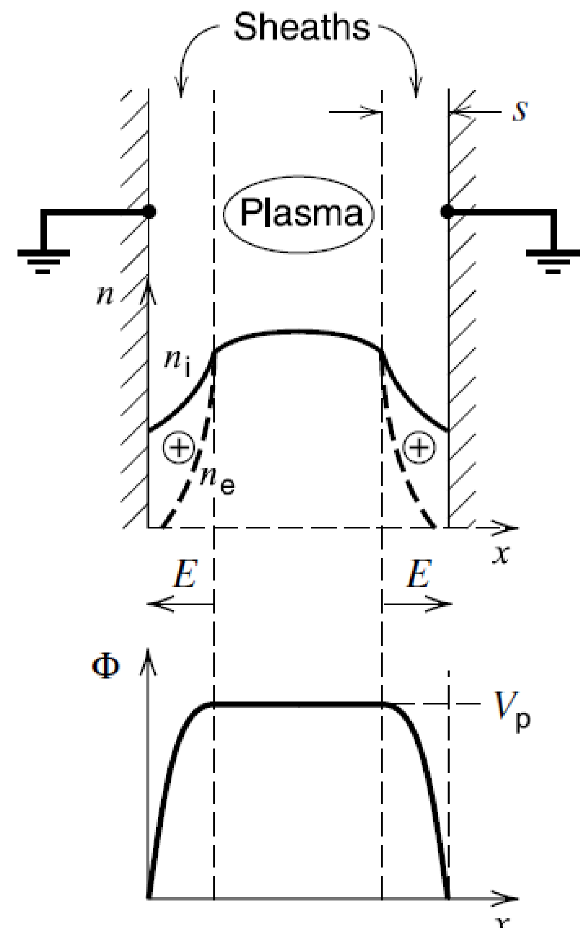
Extraction system requirements

- Optimize the beam focusing for a desired beam current and energy: low emittance (beam divergence), high perveance.
- Provide a high gas impedance to increase the gas efficiency and reduce the required vacuum pumping.
- Maximize the number of ions extracted and minimize the losses on various electrodes and by the collisions occurring in the extraction region to enhance the electrical efficiency and lengthen the lifetime of the electrodes.
- Be technically well designed; it should be well aligned, tolerate extended ion-bombardment with minimum change and have sufficient cooling. The electrode must not distort at the operating condition.
- Have a stable power system. A protective circuit is necessary to prevent damage to the power supply and electrodes when a breakdown occurs.

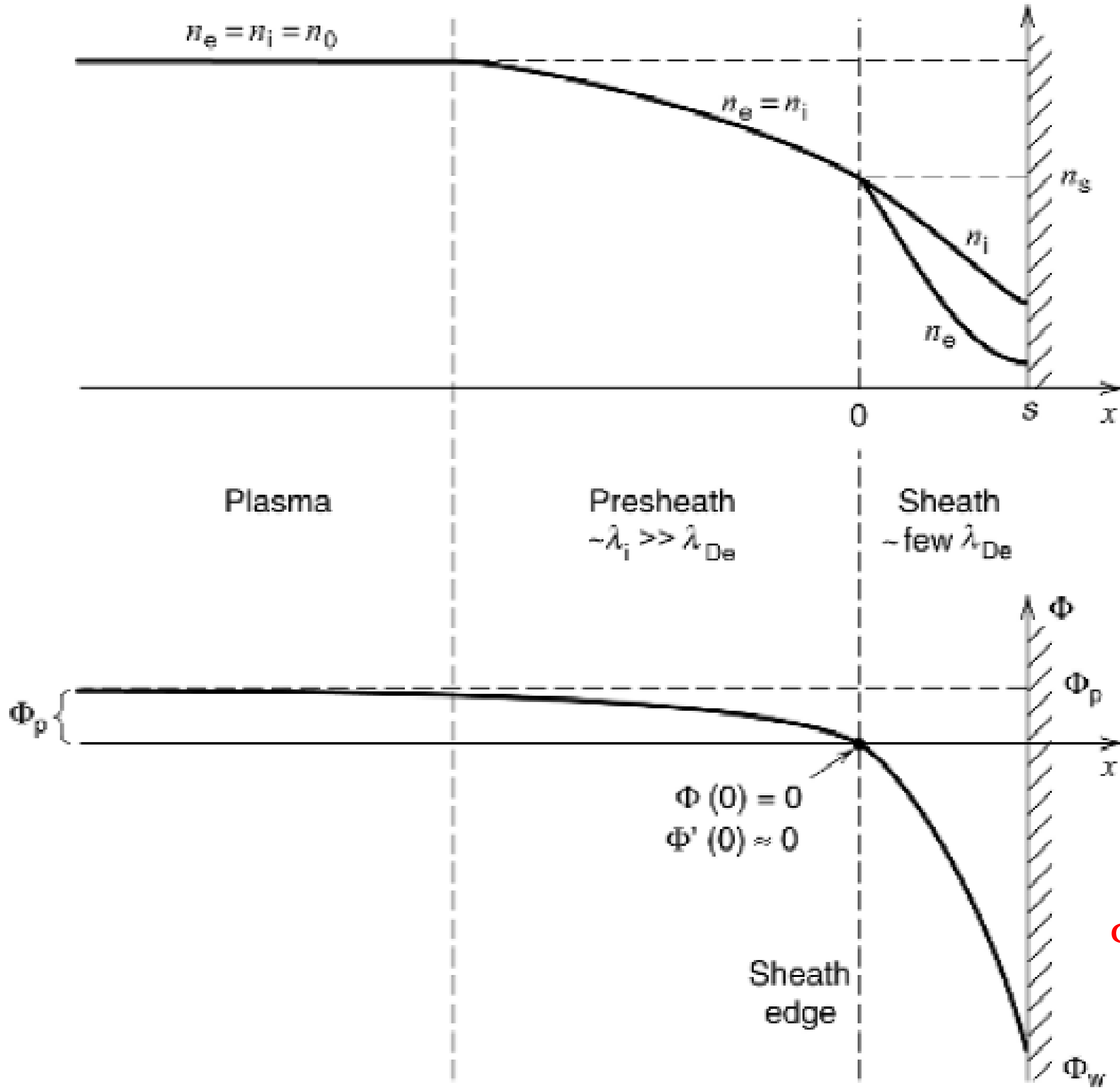
Sheath

- Plasma sheath: the non-neutral potential region between the plasma and the wall caused by the balanced flow of particles with different mobility such as electrons and ions.





Plasma-sheath structure



$$\Phi_p = \frac{\mathrm{T_e}}{2}$$

$$\Phi_w = -\frac{\mathrm{T_e}}{2}\ln\left(\frac{M}{2\pi m}\right)$$

Collisionless sheath

- Ion energy & flux conservations (no collision)

$$\frac{1}{2}Mu(x)^2 + e\Phi(x) = \frac{1}{2}Mu_s^2 \qquad n_i(x)u(x) = n_{is}u_s$$

- Ion density profile

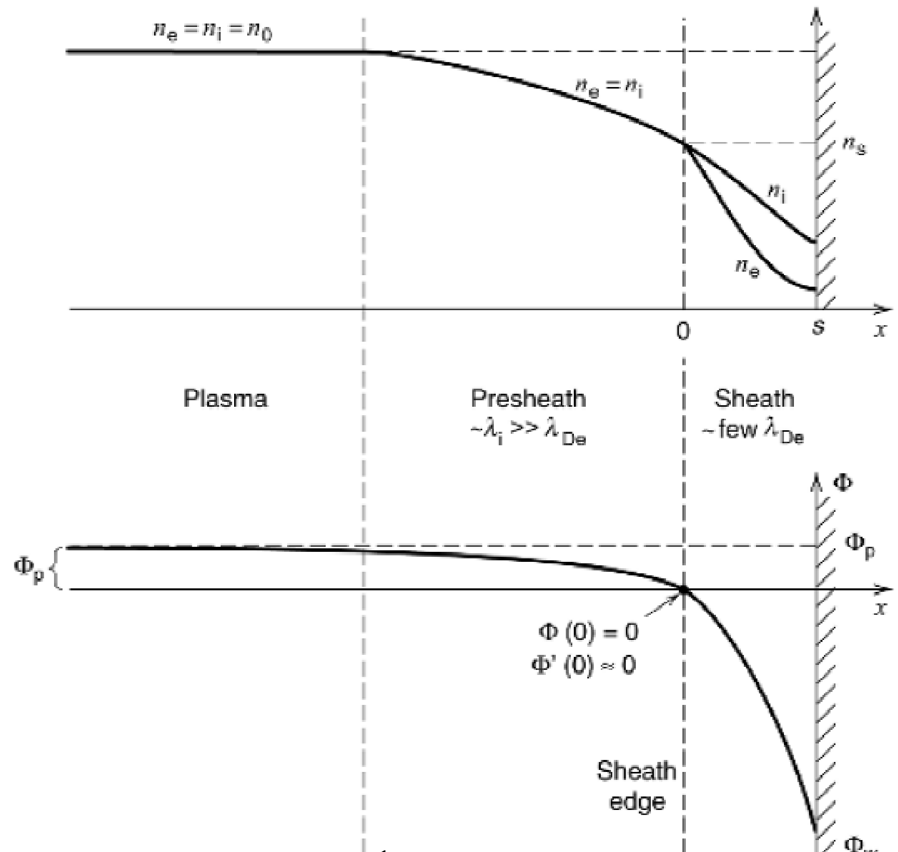
$$n_i(x) = n_{is}\left(1 - \frac{2e\Phi(x)}{Mu_s^2}\right)^{-1/2}$$

- Electron density profile

$$n_e(x) = n_{es}\exp\left(\frac{\Phi(x)}{\mathrm{T_e}}\right)$$

- Setting $n_{es} = n_{is} \equiv n_s$

$$\frac{d^2\Phi}{dx^2} = \frac{en_s}{\epsilon_0}\left[\exp\left(\frac{\Phi}{\mathrm{T_e}}\right) - \left(1 - \frac{\Phi}{\mathcal{E}_s}\right)^{-1/2}\right]$$



where, $e\mathcal{E}_s \equiv \frac{1}{2}Mu_s^2$

Bohm sheath criterion

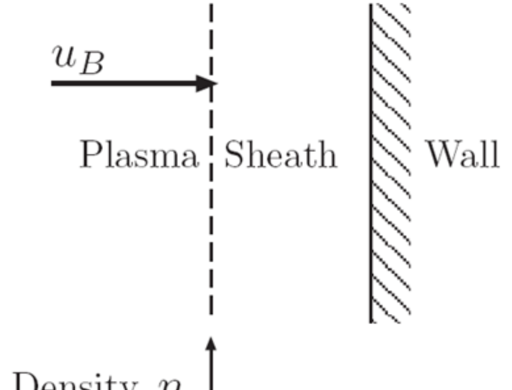
- Multiplying the sheath equation by $d\Phi/dx$ and integrating over x

$$\int_0^{\Phi} \frac{d\Phi}{dx}\frac{d}{dx}\left(\frac{d\Phi}{dx}\right)dx = \frac{en_s}{\epsilon_0}\int_0^{\Phi}\frac{d\Phi}{dx}\left[\exp\left(\frac{\Phi}{\mathrm{T_e}}\right)-\left(1-\frac{\Phi}{\mathcal{E}_s}\right)^{-1/2}\right]dx$$

- Cancelling dx's and integrating with respect to Φ

$$\frac{1}{2}\left(\frac{d\Phi}{dx}\right)^2 = \frac{en_s}{\epsilon_0}\left[\mathrm{T_e}\exp\left(\frac{\Phi}{\mathrm{T_e}}\right)-\mathrm{T_e}+2\mathcal{E}_s\left(1-\frac{\Phi}{\mathcal{E}_s}\right)^{1/2}-2\mathcal{E}_s\right]\geq 0$$

$$\Rightarrow \boxed{\mathcal{E}_s \equiv \frac{1}{2e}Mu_s^2 \geq \frac{\mathrm{T_e}}{2}}$$



- Bohm sheath criterion

$$\boxed{u_s \geq \left(\frac{e\mathrm{T_e}}{M}\right)^{1/2} \equiv \left(\frac{kT_e}{M}\right)^{1/2} \equiv u_B \quad \text{(Bohm speed)}}$$

Presheath

- To give the ions the directed velocity u_B, there must be a finite electric field in the plasma over some region, typically much wider than the sheath, called the presheath.

- At the sheath–presheath interface there is a transition from subsonic ($u_i < u_B$) to supersonic ($u_i > u_B$) ion flow, where the condition of charge neutrality must break down.

- The potential drop across a collisionless presheath, which accelerates the ions to the Bohm velocity, is given by

$$\frac{1}{2} M u_B^2 = \frac{e\mathrm{T_e}}{2} = e\Phi_p$$

where, Φ_p is the plasma potential with respect to the potential at the sheath–presheath edge

- The spatial variation of the potential $\Phi_p(x)$ in a collisional presheath (Riemann)

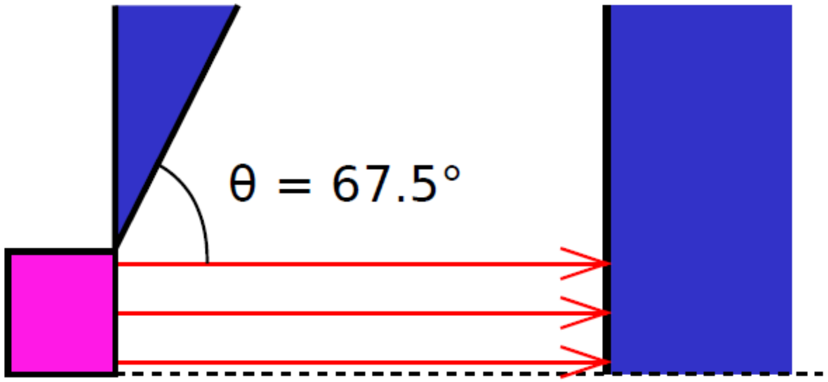
$$\frac{1}{2} - \frac{1}{2}\exp\left(\frac{2\Phi_p}{\mathrm{T_e}}\right) - \frac{\Phi_p}{\mathrm{T_e}} = \frac{x}{\lambda_i}$$

- The ratio of the density at the sheath edge to that in the plasma

$$n_s = n_b e^{-\Phi_p/\mathrm{T_e}} \approx 0.61 n_b$$

Pierce-shape extraction system

- The space-charge forces try to blow up the beam. This happens especially in the first acceleration gap because of the low velocity of the beam. To counteract the space-charge forces in the transverse direction, the electrodes can be shaped in such a way that the electric field in the first gap is not only accelerating but also focusing.
- In the case of space-charge-limited surface-emitted electrons, there is a perfect solution providing a parallel electron beam accelerated from the cathode. The solution is to have a field shaping electrode around the cathode (at cathode potential) in a 67.5° angle with respect to the emitting surface normal. This geometry is known as Pierce geometry. For plasma ion sources, there is no such magic geometry because the ions do not start from a fixed surface, but from plasma with varying starting conditions.



Ion beam extraction

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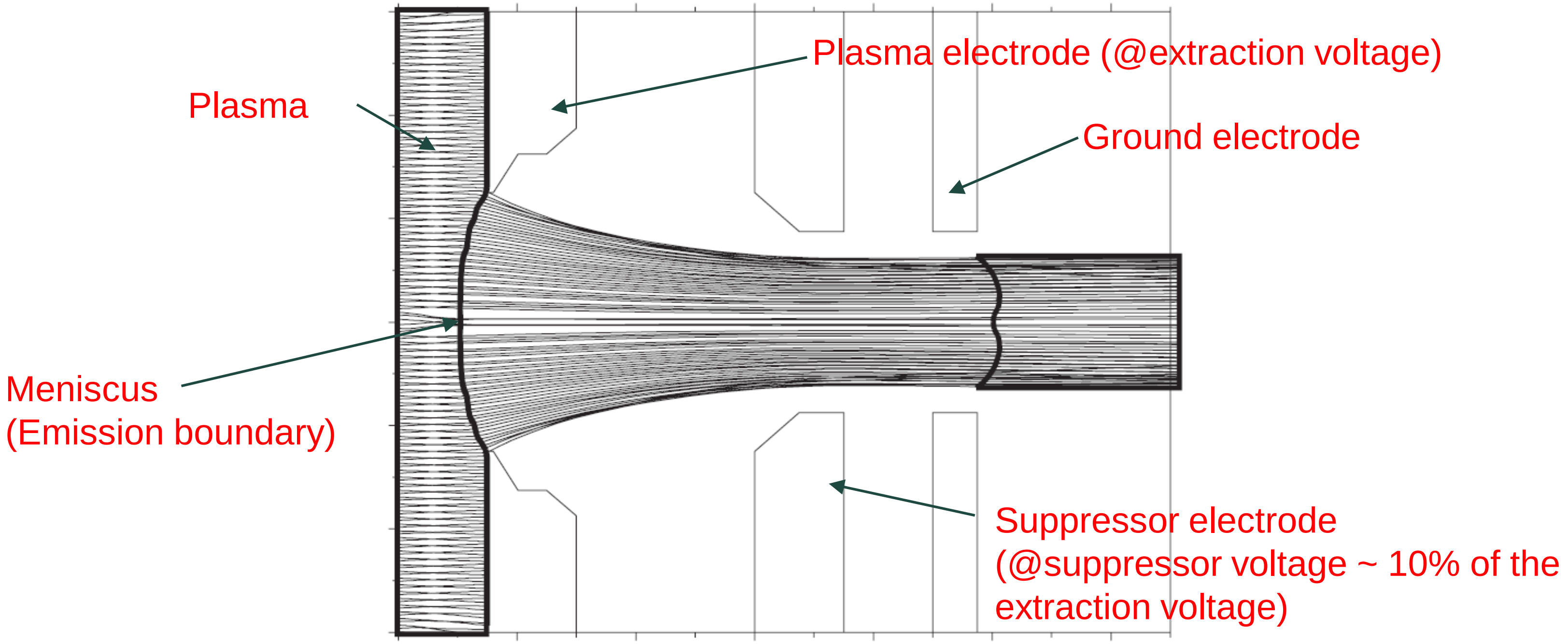
- The extraction system determines the beam properties such as ion current and beam quality in general. The extraction system thus fulfils the task of adapting the plasma generator to the beam transport system that follows.



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The “extractable flow” from an extraction system

- The extraction system of a plasma ion source is always in an emission-limited-flow regime.
- The positive ion flow region downstream from the plasma meniscus is automatically adjusted to the state that the distance between the meniscus and the electrode, the potential distribution, the flow pattern etc. are all described approximately valid by the space-charge-limited flow regime.
- Thus, in a plasma source, the shape and position of the ion-emissive surface are always automatically adjusting so that the ion flow is simultaneously emission-limited by the plasma and the space-charge limited by the extraction voltage.

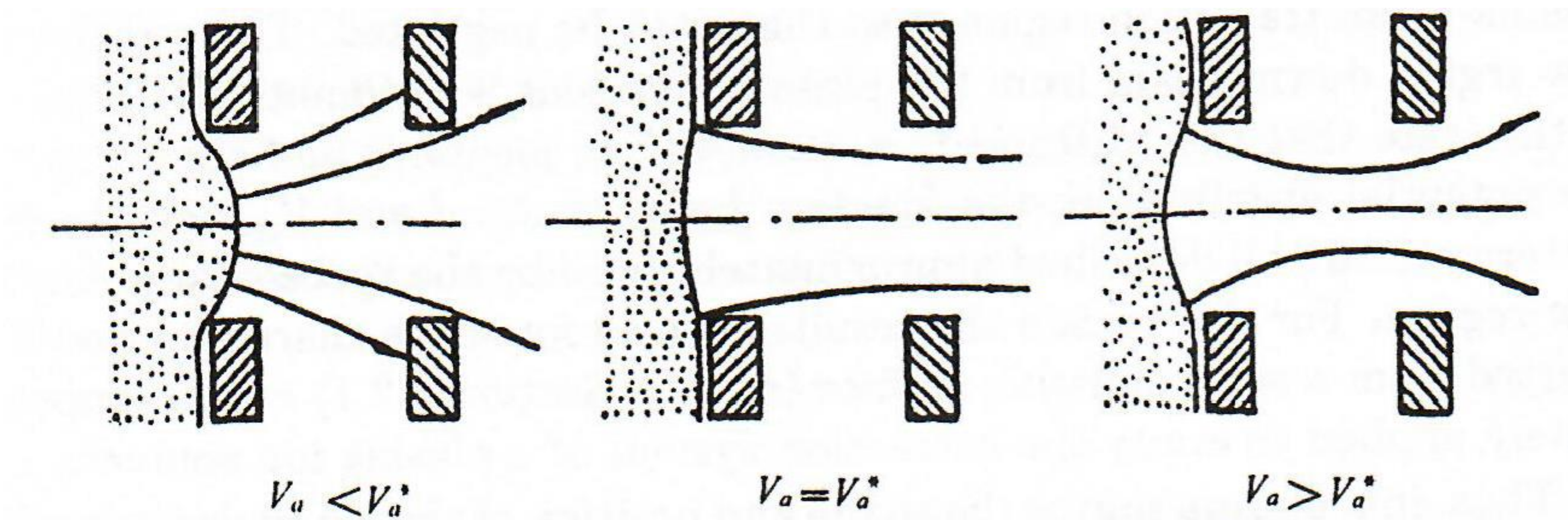
$$J_i \approx 0.6 n_0 e \left(\frac{kT_e}{M}\right)^{1/2} \approx 0.6 n_0 e \left(\frac{e\mathrm{T_e}}{M}\right)^{1/2} \approx \kappa V_a^{3/2}$$

κ: a factor determined by the geometry of the extraction system including the shape of the meniscus

Adjustment of ion emissive surface

- Minimum divergence: The beam is initially convergent from a concave meniscus in order to cancel the divergence caused by the space charge expansion and the extraction aperture lens leading to a parallel output beam → optimum focusing or optimum matching.
- The optimum matching is obtained at a certain value of $I/V_a^{3/2}$, called the optimum perveance, P^* (for constant J_i, $V_a = V_a^*$).

Under-focus | Optimum matching | Over-focus



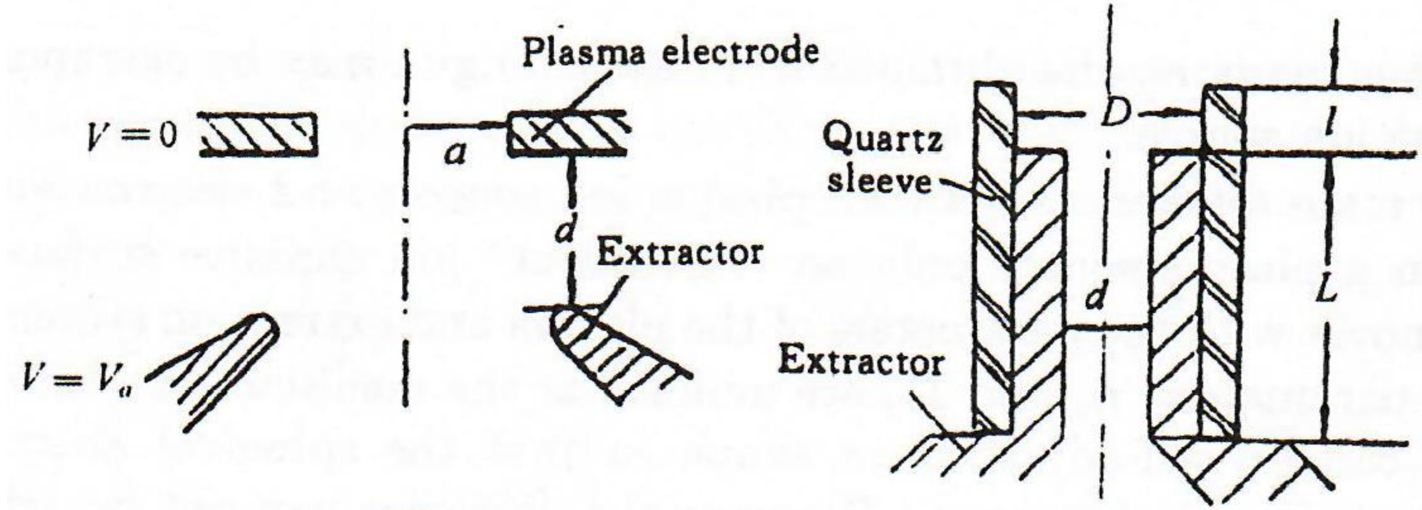
Comparison between a plasma ion source and an electron gun extraction system

- If the plasma parameters are uniform at the meniscus, the ion emissive surface can be self-adjusting in shape so that the spherical aberration is less than in an electron gun. However, the meniscus cannot be arbitrarily shaped as in an electron gun and the deformation of the field at the plasma electrode edge will cause an aberration. Moreover, there frequently exist a non-uniformity and an oscillation of n_e and/or T_e, which will generate a deformation and an oscillation of the meniscus resulting in a deterioration of ion optics.
- The initial conditions at the emissive surface are different. The beam current from the ion-emissive surface is independent of the extraction voltage and the geometry. Ions have directional drift energy when they arrive at the meniscus.
- Different space charge effects occur, since the mass of ions is much greater than that of electrons. Neutralization effect of the plasma electrons cannot be neglected.
- Electron beam is extracted in vacuum. In plasma ion sources, several ion species are generally extracted and travel in a low vacuum, producing other parasitic phenomena in the ion-extraction zone, e.g. ionization, charge exchange, particles impacting on the electrodes, backstreaming of secondary electrons, etc. Therefore, it may be difficult to get a very high extraction field.

Geometry of extraction systems

- Two-electrode system

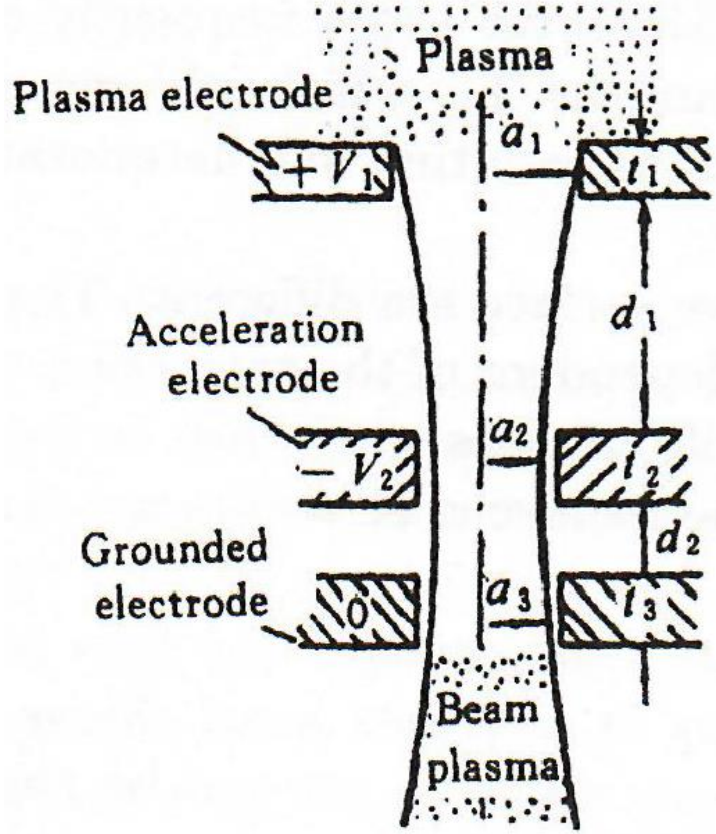
  - 1st electrode (plasma electrode, emitting electrode, focusing electrode) is used to fix the plasma potential. Its function is to determine the size and shape of the emissive aperture and to determine the circumference of the plasma meniscus. The shape of this electrode plays an important role in beam focusing.
  - 2nd electrode (extractor, accelerating electrode, grounded electrode) is at negative potential relative to the plasma for positive ion sources. The beam performance is not very sensitive to the shape of the 2nd electrode.



Geometry of extraction systems

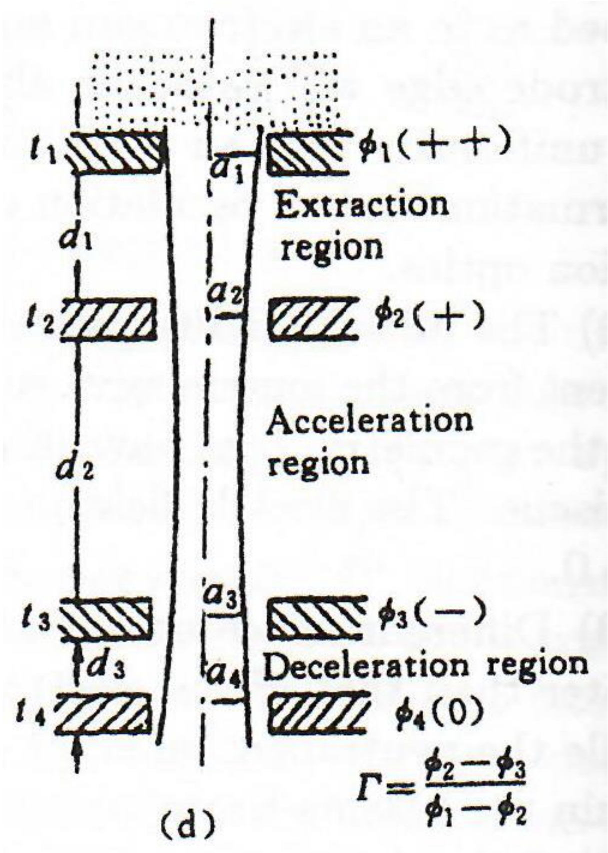
- Three-electrode system (accel-decel system or triode system)
  - 3rd electrode (ground electrode, deceleration electrode) is at ground.
  - 2nd electrode (extraction electrode, acceleration electrode, suppression electrode) is held negative with respect to ground.

- The functions of this configuration are:
  - To suppress electrons back to the source (reduce power consumption, assist space-charge neutralization)
  - To change ion beam current at a constant extracted beam energy by varying the potential of the acceleration electrode.
  - To obtain high-current beams at low energy by using a high acceleration voltage and then decelerating the ions to ground.



Geometry of extraction systems

- Four-electrode system (extraction-accel-decel system or tetrode system)
  - The three electrode system is limited in beam energy to several tens of kV due to power loading on the electrodes and high-voltage holding ability. For high energy beams, four-electrode system is commonly used.

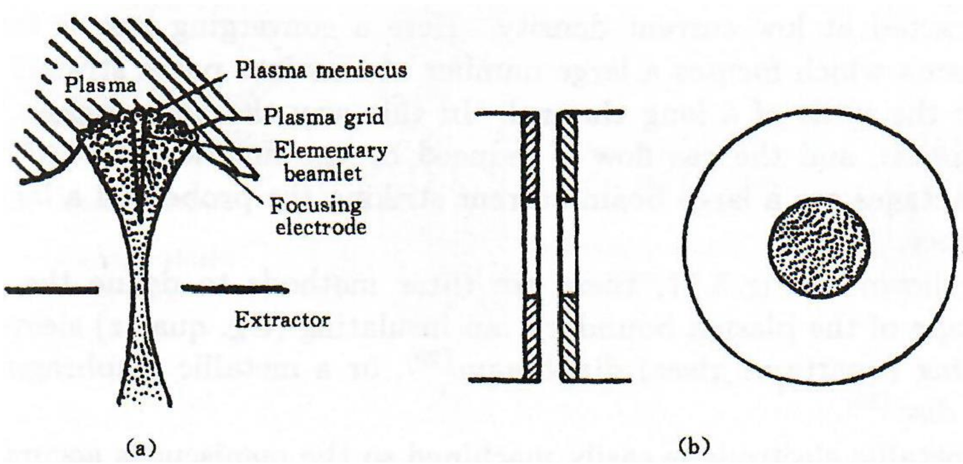


Geometry of extraction systems

- According to the shape of the extraction aperture: circular or slit aperture
- The advantage of slit system:
  - The ion beam may be increased in proportion to the slit length keeping the beam focusing optics unchanged.
  - The divergence along the slit is usually small.
  - The electrode deformation caused by thermal expansion needs to be considered in only one direction.
  - The multi-slit system gives higher transparency and easier cooling by water tubes.
  - Wires or metal sheets may be used for slit electrodes.

Geometry of extraction systems

- To relatively fix the shape and position of the emissive surface, a spherical grid can be used as a plasma electrode for a large extraction aperture.
- The advantage of a grid system:
  - The shape of the emissive surface remains fixed and essentially independent of the discharge parameters and extraction voltage.
  - The plasma is shielded from interference from the extraction field.
  - A two grid system reduces the divergent effect and increases the extraction field.
  - It is only used in pulsed ion sources (heating, deformation)

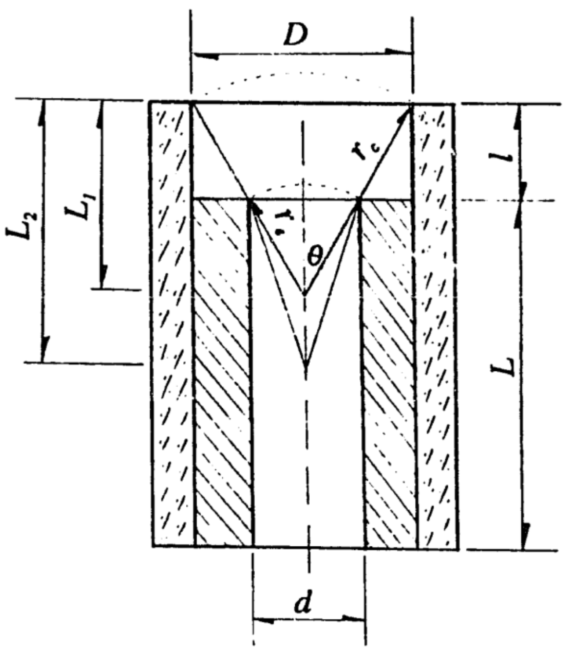


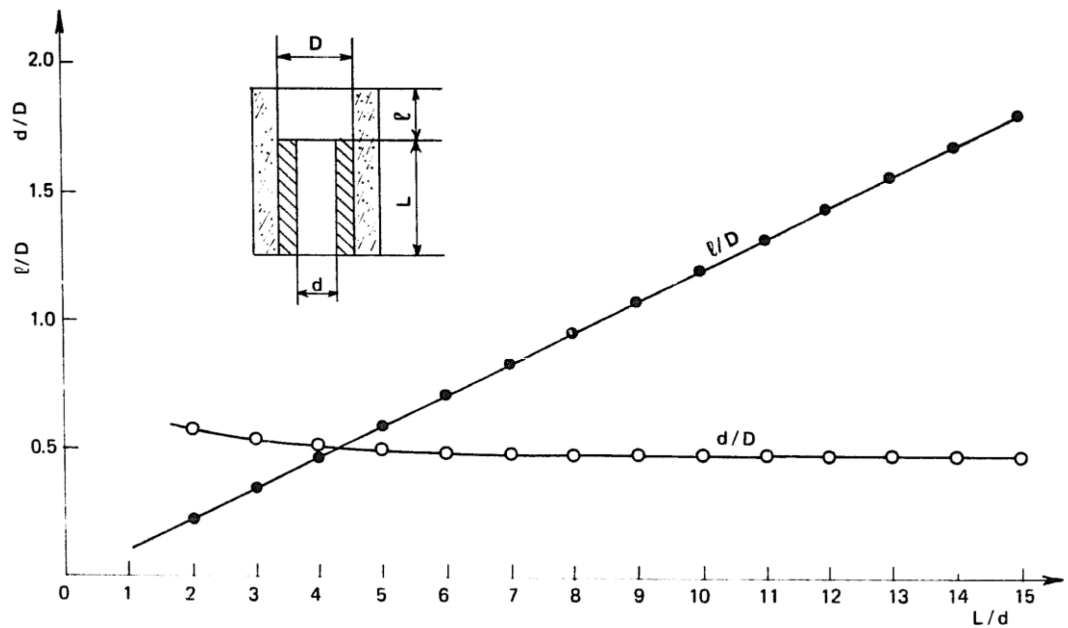
Probe extraction systems for low plasma density

- Low plasma density: 10^{10} - 10^{11} cm^{-3}
- The optimum geometry (minimum divergence) is given by

$$\frac{D}{d} \approx 1.8 - 2.2, \qquad \frac{l}{d} \approx 0.5 - 1, \qquad \frac{L}{d} \approx 4 - 6$$

$$l/D = 0.122\, L/d \qquad D = \left[\frac{I_i \sqrt{m_i} \times 10^{13}}{23.12\, n_i \sqrt{T_e} \left[1 + \frac{1}{\tan^2\theta} \left(1 - \sqrt{1 + \tan^2\theta} \right) \right]} \right]^{1/2}$$

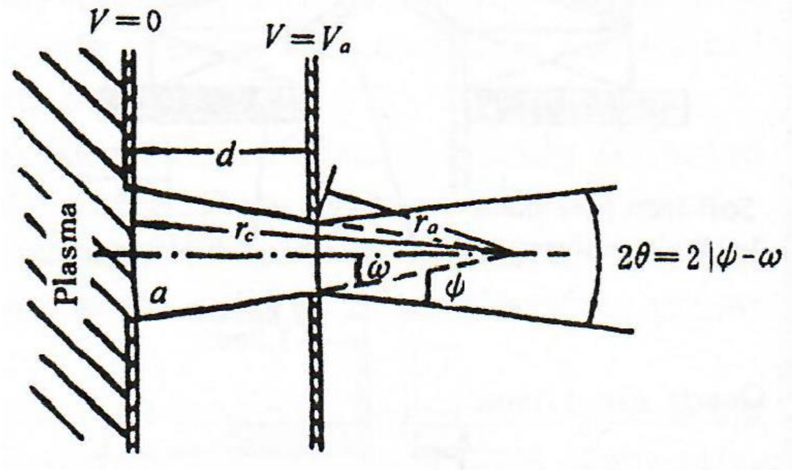




NIM A288, 303 (1990)

Aperture extraction systems: analytic model for a two-electrode system

- The SCL current in spherical geometry:



$$I = \frac{4\epsilon_0}{9}\sqrt{\frac{2ze}{m_0}}\frac{4\pi V_a^{3/2}}{\alpha(r_c/r_a)^2}$$

- For small $d = r_c - r_a$,

$$P = \frac{I}{V_a^{3/2}} \approx 1.71 \times 10^{-7}\frac{a^2}{d^2}\left(1 - 1.6\frac{d}{r_c}\right)\sqrt{\frac{z}{A}}$$

$$P = \frac{I}{V_a^{3/2}} \approx P_0\left(1 - 1.6\frac{d}{r_c}\right) \Rightarrow r_c \approx 1.6\left(\frac{P_0}{P_0 - P}\right)d$$

- One can relate the initial convergence (or divergence), ω, with the beam perveance:

$$\omega \approx \frac{a}{r_c} \approx 0.625\frac{a}{d}\left(1 - \frac{P}{P_0}\right)$$

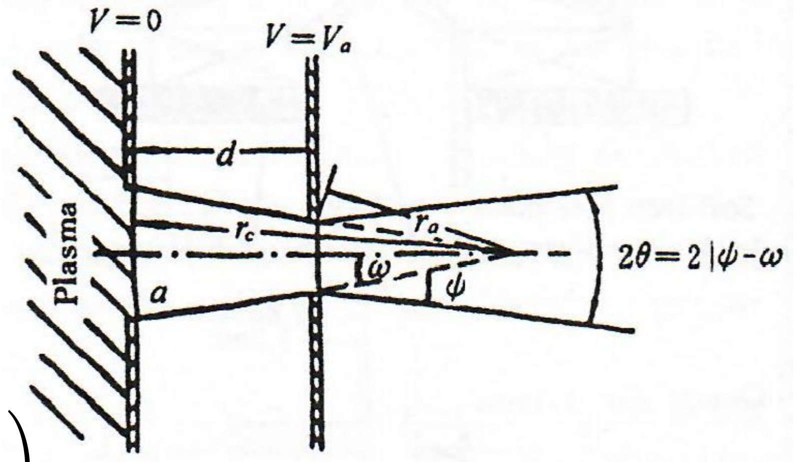
RSI 44, 1258 (1973)

Aperture extraction systems: analytic model for a two-electrode system

- Lens effect: The extractor separates two regions, one of longitudinal electric field almost equal to zero in the drift space and one of longitudinal field, E equal to V_a/d, in the accelerating gap. Between the regions there must be a transverse electric field and this causes the beam to diverge.

$$f \approx \frac{4V_a}{E_2 - E_1} \approx -\frac{4V_a}{E_a} \approx 3d$$

$$\tan\psi \approx \psi \approx \frac{b}{3d} \approx \frac{a - \omega d}{3d}$$



- One obtain final beam divergence angle:

$$\theta \approx \omega - \psi \approx \omega - \frac{a - \omega d}{3d} \approx 0.5\frac{a}{d}\left(1 - 1.67\frac{P}{P_0}\right)$$

→ When $\theta > 0$, the ejected beam is convergent; $\theta < 0$, divergent; and $\theta = 0$, the beam is parallel.

- The optimum perveance P^*:

$$P^* \approx \frac{P_0}{1.67} \approx 0.6P_0$$

Aperture extraction systems: analytic model for a two-electrode system

- One can obtain more accurate values of E taking into account the effect of the convergence of the beam

$$\tan\psi \approx \psi \approx \frac{a}{3d}$$

- Then the beam divergence angle and the optimum perveance:

$$\theta \approx 0.29\frac{a}{d}\left(1 - 2.14\frac{P}{P_0}\right)$$

$$P^* \approx 0.47 P_0$$

→ Better agreement with experiments ($P^* \approx 0.4\ P_0$)

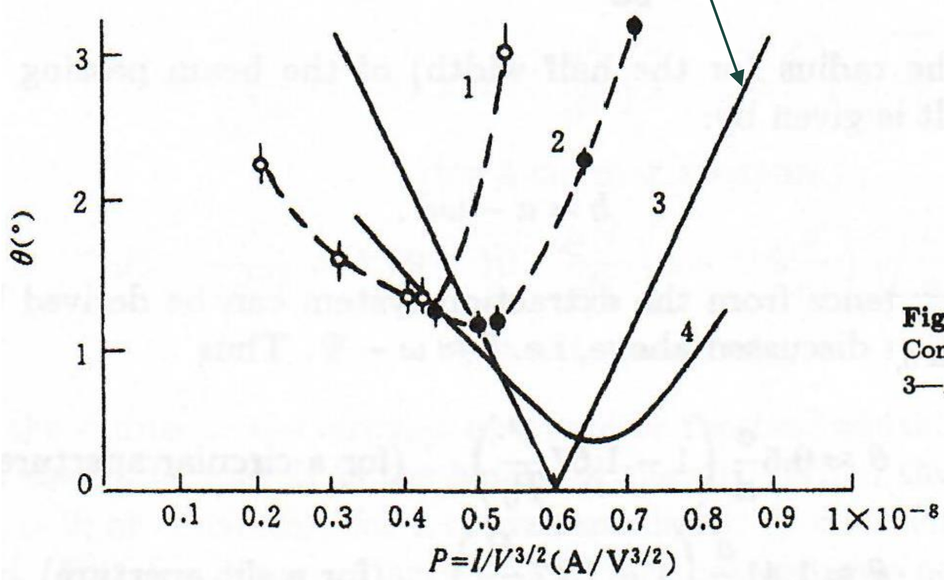


Fig. 3.13. Variation of the beam divergence with beam perveance [37]. 1—Constant V_a, with variable arc current, I_A. 2—Constant I_A, with variable V_a. 3—Analytic model calculation. 4—Numerical analog ($s_1 = \frac{a}{d} = 0.33$).

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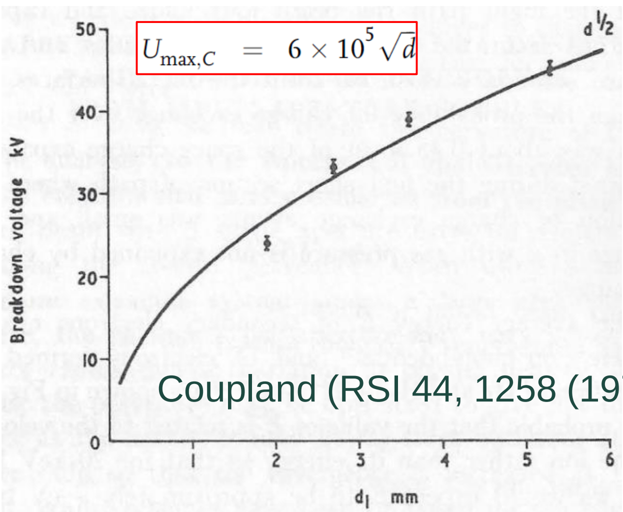
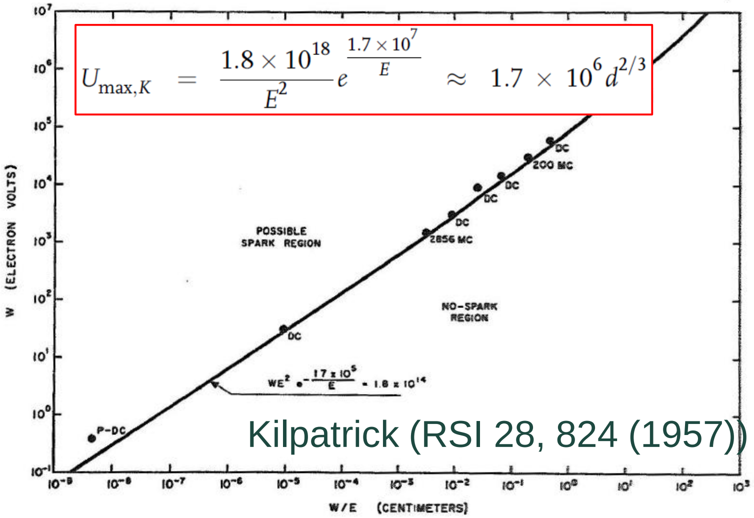
Aperture extraction systems: characteristics and design procedure

- For a given extraction geometry, the divergence depends only on the beam perveance. Thus, when the plasma density varies as $V_a^{3/2}$, the optical performance of the extracted beam is unchanged, while the extracted beam current varies as $V_a^{3/2}$.
- The optimum beam perveance increases proportionally with the perveance of the planar extraction geometry ($P^* \propto P_0$) and hence the square of the aspect ratio ($P^* \propto (a/d)^2$).
- In the environment of a plasma source, the breakdown voltage across the gap can be expressed by the equation [Coupland or Kilpatrick]:

d is in meters



Coupland (RSI 44, 1258 (1973))



Kilpatrick (RSI 28, 824 (1957))

Aperture extraction systems: characteristics and design procedure

- By taking the Coupland breakdown voltage law, we obtain the maximum current density for a proton beam corresponding to the optimum perveance (minimum divergence):

$$J_{max} = \frac{I_{max}}{\pi a^2} \approx 3.3 \times 10^{11}\, V_a^{-5/2} \quad (\mathrm{A/cm^2})$$

- In multi-aperture ion sources, if the extraction system is operated so that the beamlet from the central aperture is optimum ($P = P^* = 0.47P_0$), and the maximum difference in the plasma density among the apertures is Δn_e; the beam divergence generated by the difference in the plasma density can be deduced as:

$$\Delta\theta \approx 16.6\, \frac{a}{d}\left(\frac{\Delta n_e}{n_e}\right) \quad (°)$$

→ For a high-perveance extraction geometry, the divergence of the beam varies rapidly around minimum for a small change in the beam perveance.

Circular three-electrode extraction system

- Usually $V_1 \gg |V_2|$, so the effect of the deceleration gap on the beam optics is negligible. Hence, two-electrode system may be extended.
- Divergence for proton beam:

$$\theta \approx \sqrt{\frac{kT_i}{V_a}} + 0.2s_1\left(1 - \frac{2.25P}{1.2 \times 10^{-7}s_1^2}\right) + 5 \times 10^6 s_2 P \text{ [rad]}$$

- Aspect ratio, $s_1 = a_1/d_1$

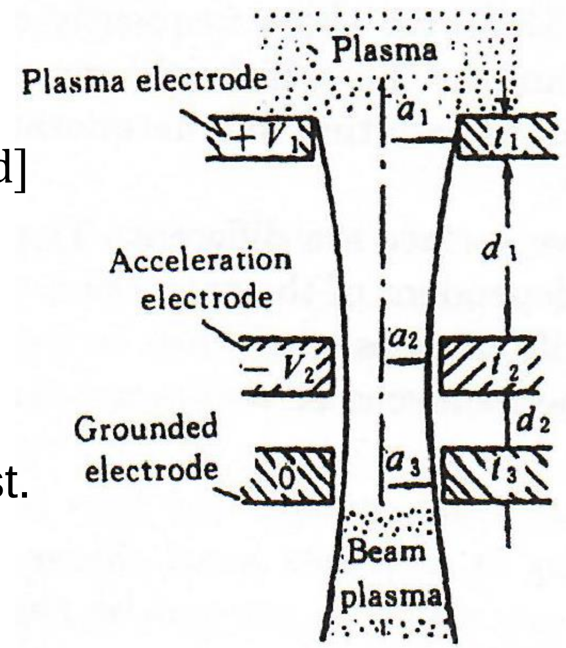
$$P^* \approx 0.4P_0 \propto s_1^2$$

  - Numerical analysis indicates that $s_1 = 0.8$ is the best.
  - It is better to use an effective gap distance

$$d_{eff} = d_1 + t_1 + 0.8a_2$$

- Acceleration gap, d_1
  - As short as possible, avoiding vacuum breakdown

$$d \approx 2.8 \times 10^{-10}\,(V_1 + |V_2|)^2$$

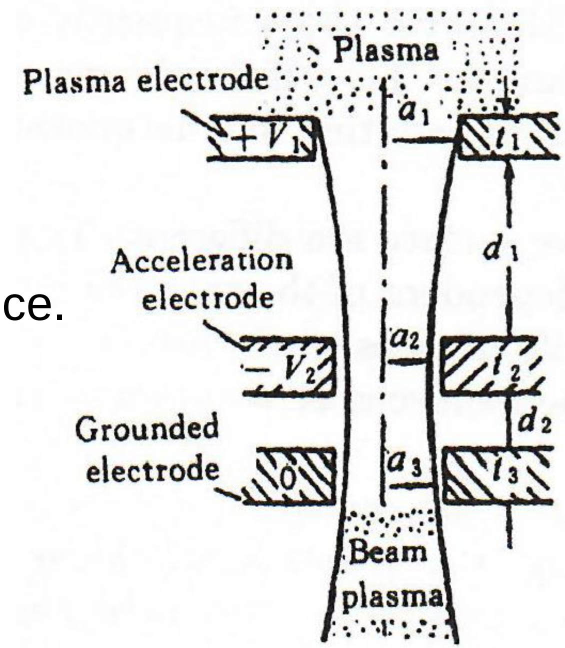


$$s_1 = a_1/d_1$$

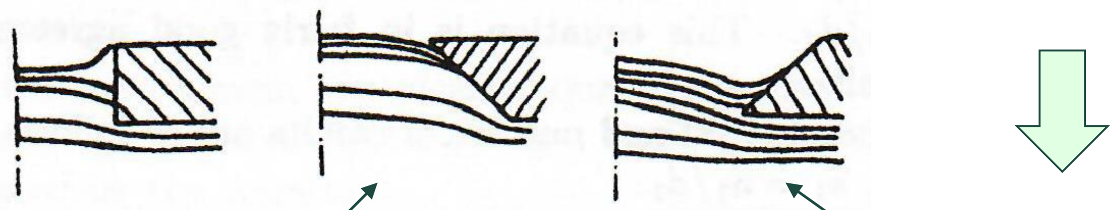
$$s_2 = a_2/d_2$$

Circular three-electrode extraction system

- Thickness of the plasma electrode, t_1
  - For a large value of t_1, the extracted current density decreases, because the extraction field cannot penetrate deeply into the aperture. Also, a serious aberration is caused by the edge effect.
  - For a small value of t_1, a satisfactorily shaped meniscus is not possible, increasing beam divergence. The gas consumption increases. The rim of the electrode is easily destroyed.
  - Optimum values: $t_1/a_1 \approx 0.5\sim1$, $t_1 \approx 0.2d_1$



- Aperture shape of plasma electrode



Smaller minimum divergence

Higher transmission

Expansion cup extraction systems for high plasma density

- When the plasma density is very high, as in the duoplasmatron where $n_e \approx 10^{14}\ \mathrm{cm}^{-3}$, the emissive ion current density is so high ($J_i \approx 10^2\ \mathrm{A\ cm}^{-2}$) that the meniscus remains outside the source and seriously convex even at an extraction voltage of breakdown level. This results in an unacceptably large divergence.
- To reduce the plasma density at the meniscus, an expansion cup extraction system is used.

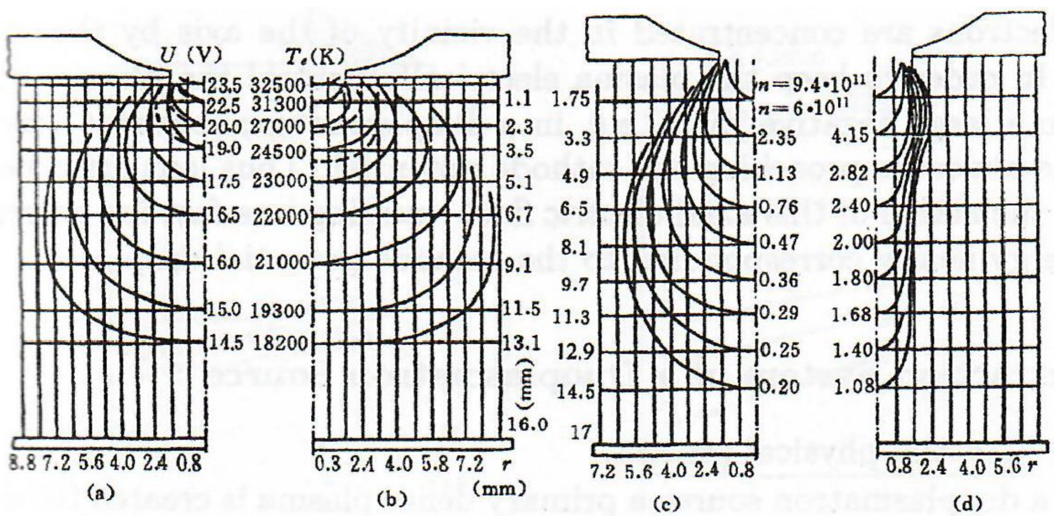


Fig. 3.16. Diagram of the properties of a diffusing plasma [66]. (a) Spatial potential distribution. (b) Spatial distribution of electron temperature. (c) Spatial density distribution in magnetic-field-free space. (d) Spatial density distribution in the space with a magnetic field.

Example: use of expansion cup