Extraction Systems for Ion Sources

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Introduction

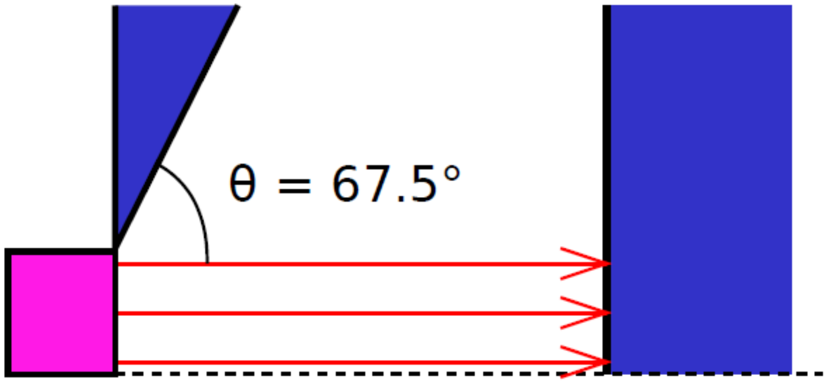
- In general, an ion source consists of two parts. The first is the plasma generator that provides ion production and thus serves as an ion reservoir. The second is the extraction system for accepting ions from the reservoir and forming an ion beam.
- Both parts of the source may be treated independently 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.

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.



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.

$$J_i \approx 0.61 n_0 e \left(\frac{kT_e}{M}\right)^{1/2} \approx \kappa V_a^{3/2}$$

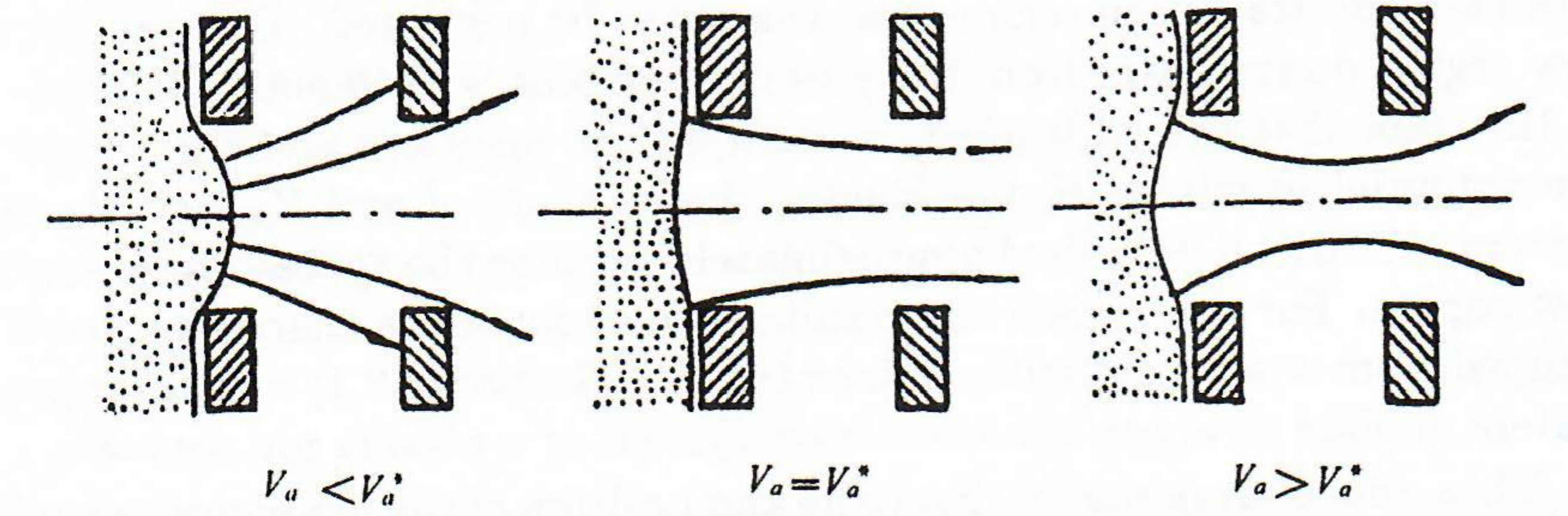
κ: a factor determined by the geometry of the extraction system including the shape of the meniscus

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.

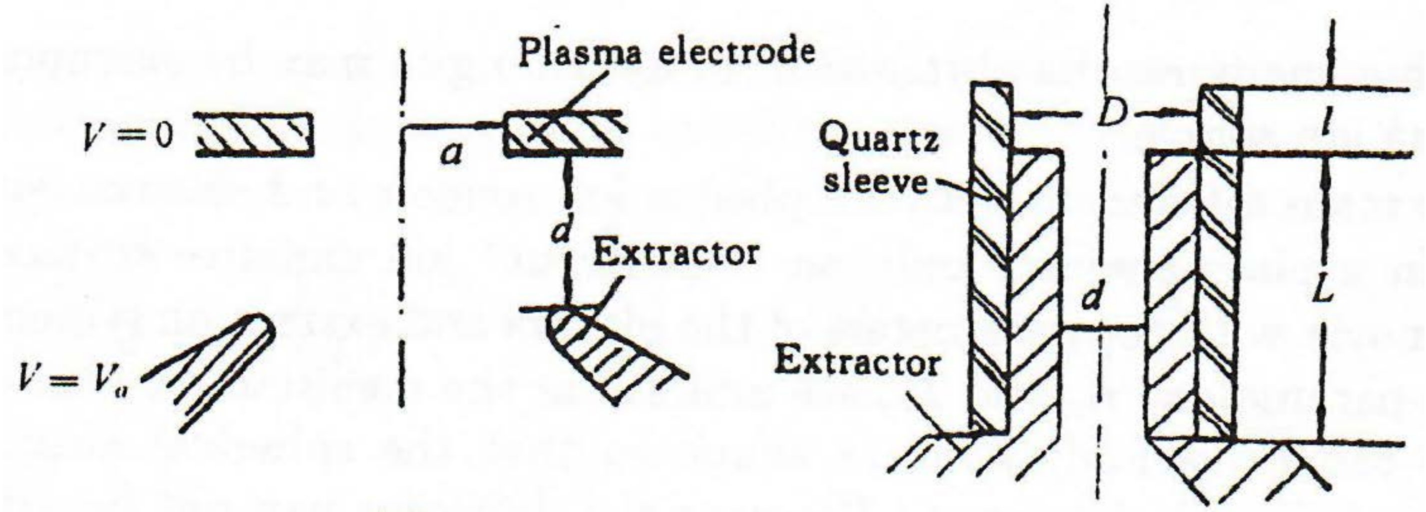
- Electron beam is extracted in vacuum. In plasma ion sources, several ion species are generally extracted and travel in a low vacuum, producing other parasitic phenomena in the ion-extraction zone, e.g. ionization, charge exchange, particles impacting on the electrodes, backstreaming of secondary electrons, etc. Therefore, it may be difficult to get a very high extraction field.

Geometry of extraction systems

- Two-electrode system

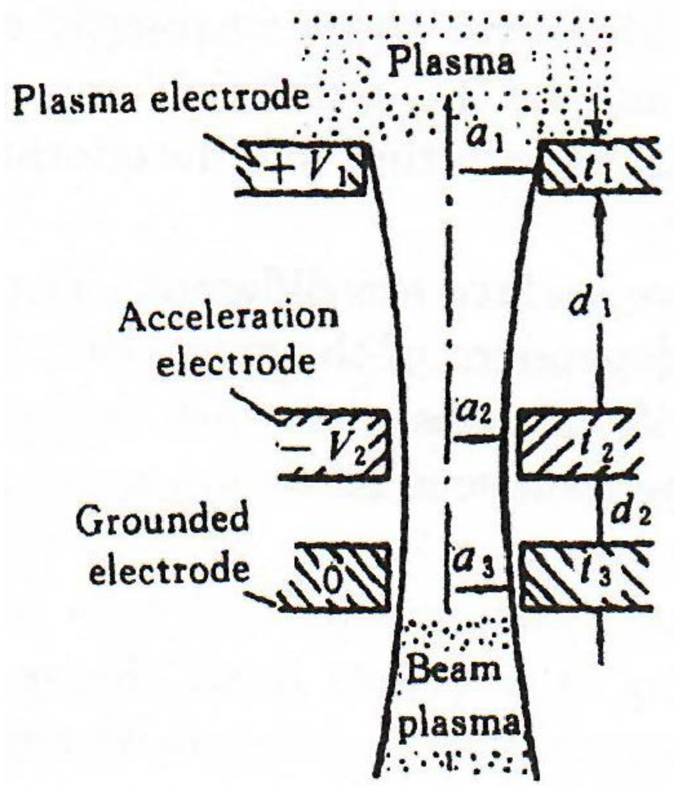
  - 1^{st} electrode (plasma electrode, emitting electrode, focusing electrode) is used to fix the plasma potential. Its function is to determine the size and shape of the emissive aperture and to determine the circumference of the plasma meniscus. The shape of this electrode plays an important role in beam focusing.

  - 2^{nd} 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 2^{nd} electrode.



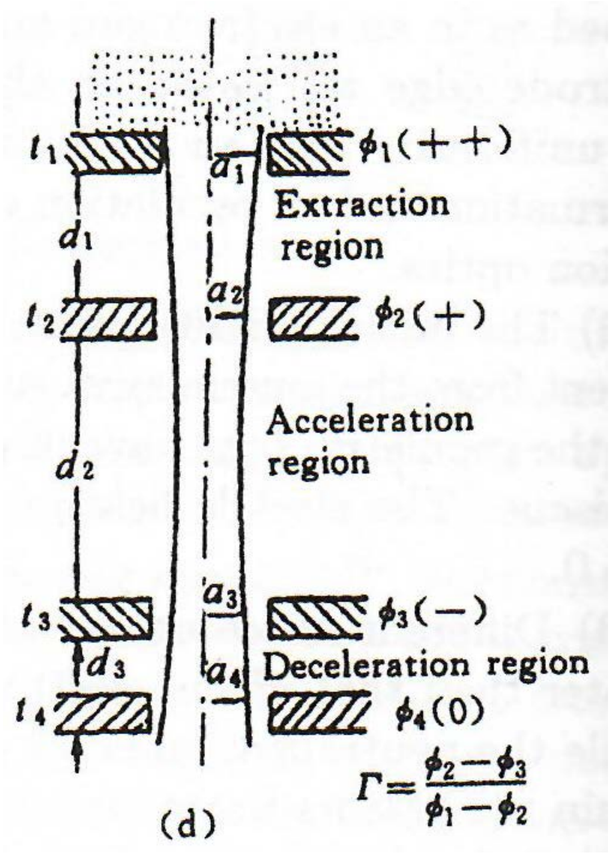
Geometry of extraction systems

- 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.

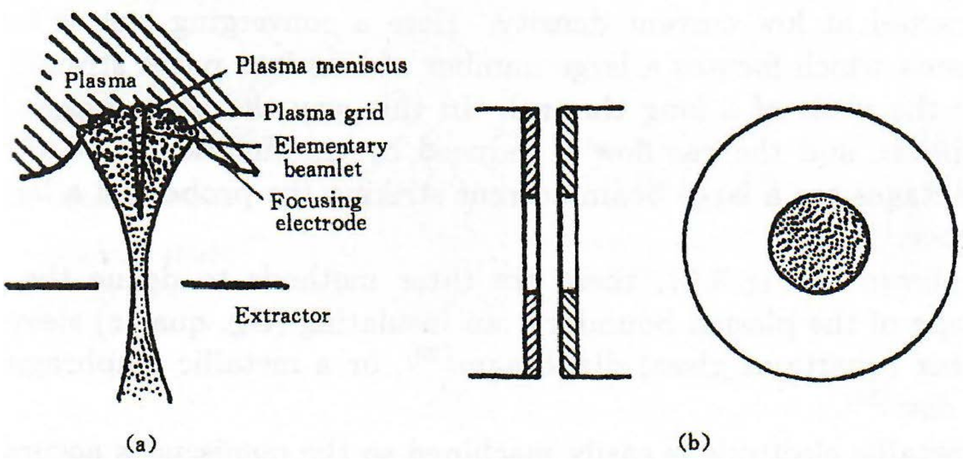


Geometry of extraction systems

- 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)

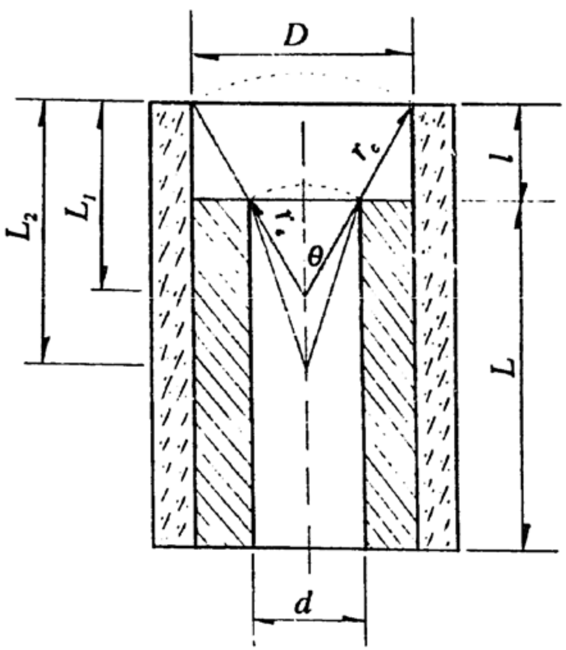


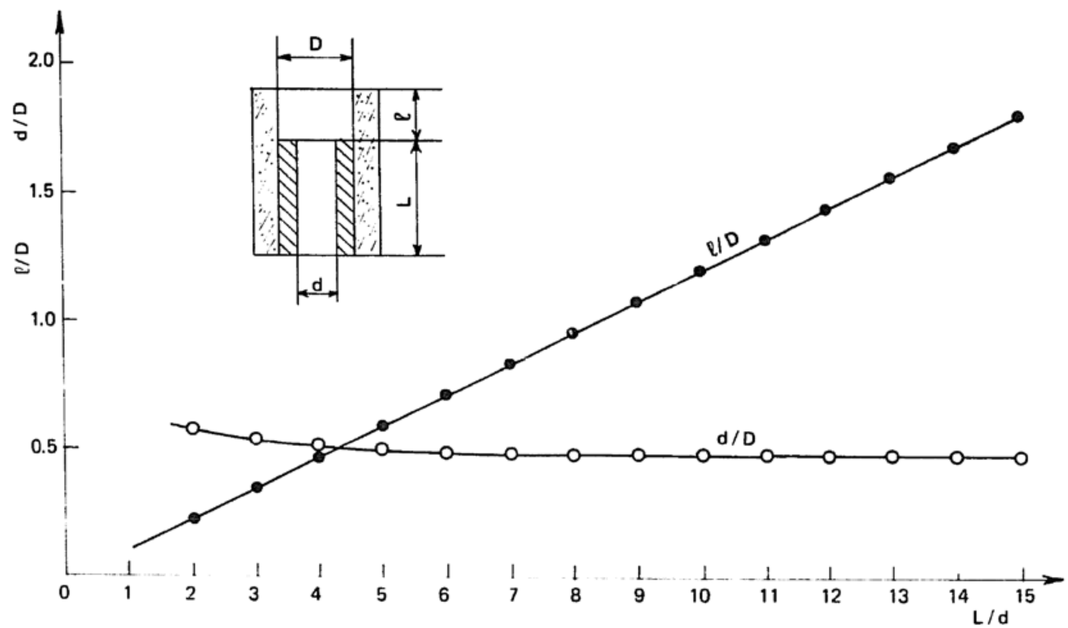
Probe extraction systems for low plasma density

- 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

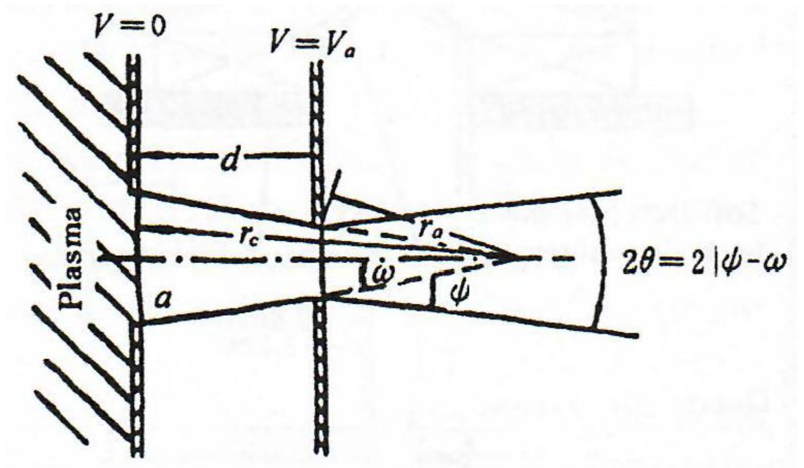
- The SCL current in spherical geometry:

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

- For small $d = r_c - r_a$,

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

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



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

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

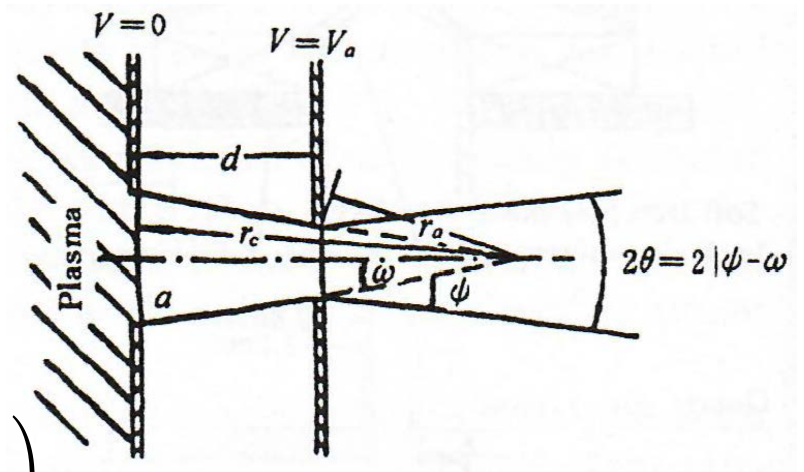
RSI 44, 1258 (1973)

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:

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

→ Better agreement with experiments

$$P^* \approx 0.47P_0$$

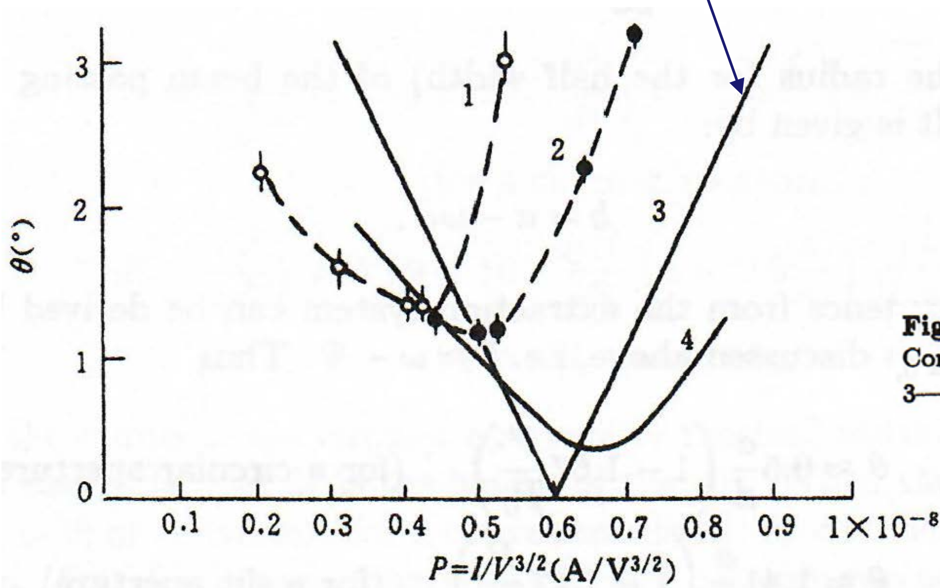


Fig. 3.13. Variation of the beam divergence with beam perveance [37]. 1—Constant V_a, with variable arc current, I_A. 2—Constant I_A, with variable V_a. 3—Analytic model calculation. 4—Numerical analog ($s_1 = \frac{a}{d} = 0.33$).

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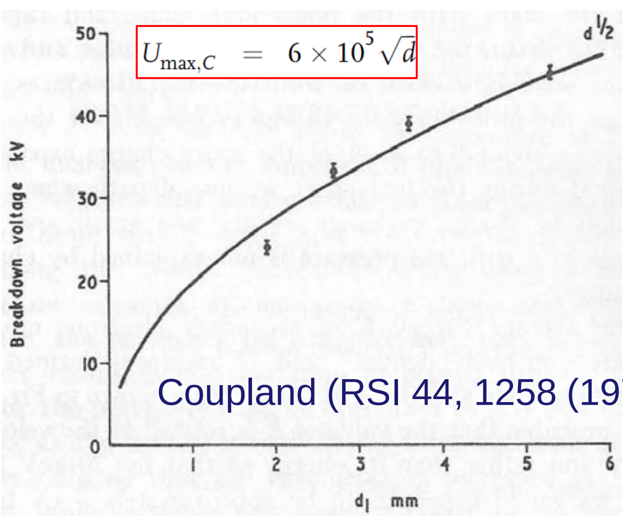
Aperture extraction systems: characteristics and design procedure

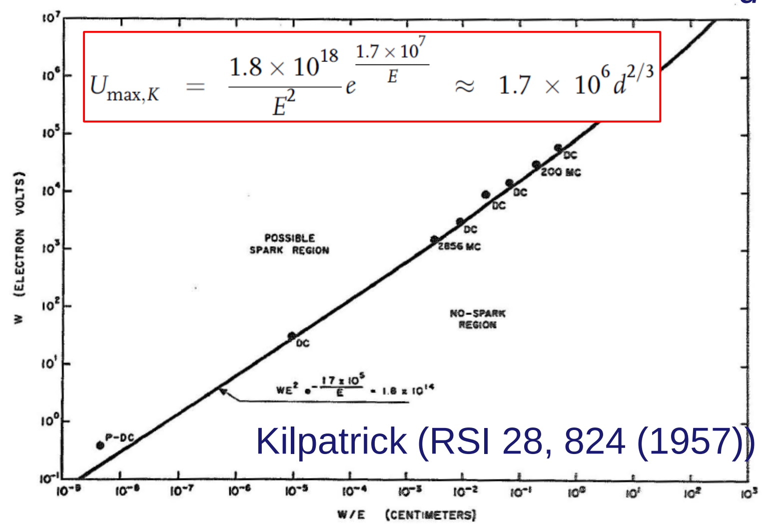
- For a given extraction geometry, the divergence depends only on the beam perveance. Thus, when the plasma density varies as $V_a^{3/2}$, the optical performance of the extracted beam is unchanged, while the extracted beam current varies as $V_a^{3/2}$.
- The optimum beam perveance increases proportionally 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



$$U_{\max,C} = 6 \times 10^5 \sqrt{d}$$

Coupland (RSI 44, 1258 (1973))



$$U_{\max,K} = \frac{1.8 \times 10^{18}}{E^2} e^{\frac{1.7 \times 10^7}{E}} \approx 1.7 \times 10^6 d^{2/3}$$

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):

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

- 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:

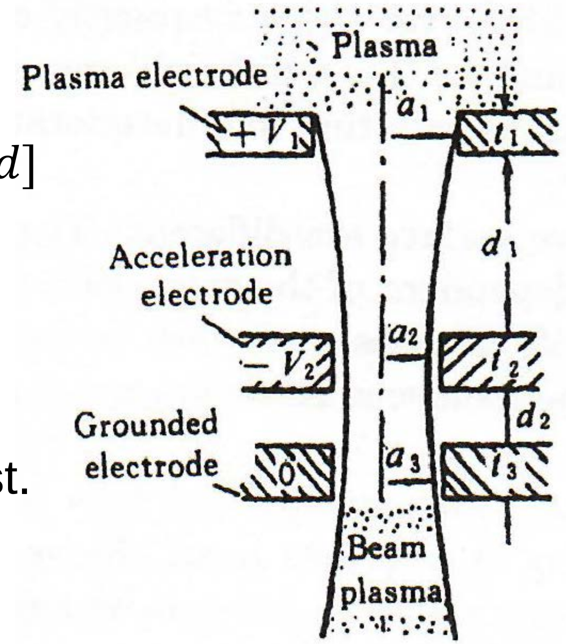
$$\Delta\theta \approx 16.6\, \frac{a}{d}\left(\frac{\Delta n_e}{n_e}\right) \;\; (°)$$

→ 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:

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



- 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

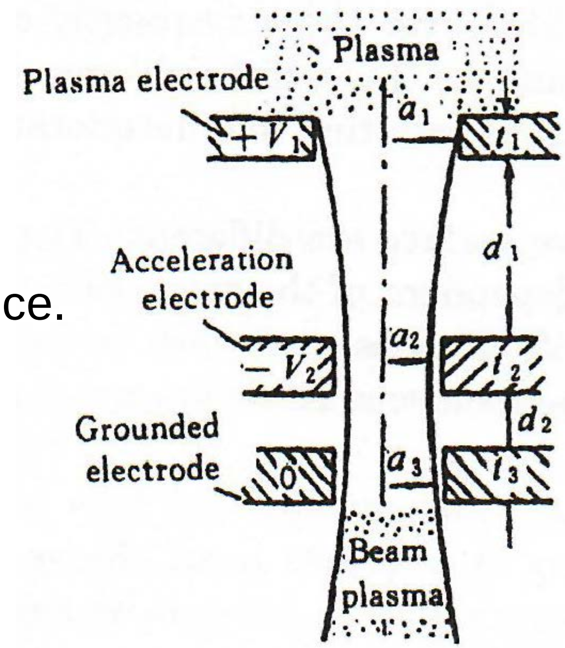
$$d \approx 2.8\times 10^{-10}\,(V_1 + |V_2|)^2$$

$$s_1 = a_1/d_1$$

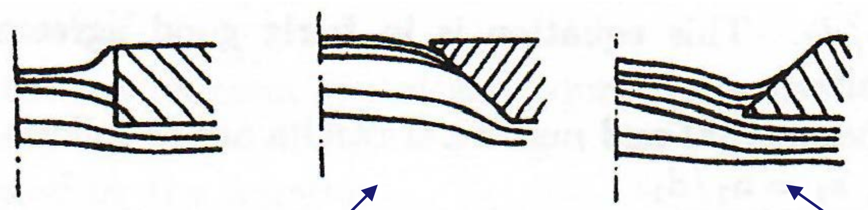
$$s_2 = a_2/d_2$$

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 $n_e \approx 10^{14} cm^{-3}$, the emissive ion current density is so high ($J_i \approx 10^2 Acm^{-2}$) 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.

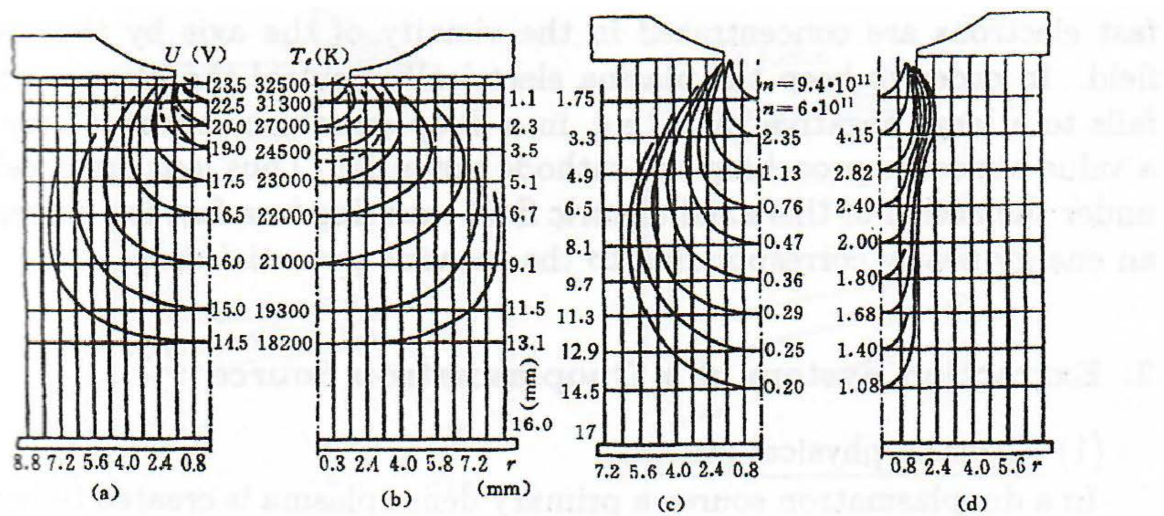


Fig. 3.16. Diagram of the properties of a diffusing plasma [66]. (a) Spatial potential distribution. (b) Spatial distribution of electron temperature. (c) Spatial density distribution in magnetic-field-free space. (d) Spatial density distribution in the space with a magnetic field.