Elementary Ion Sources

Fall, 2017

Kyoung-Jae Chung

Department of Nuclear Engineering

Seoul National University

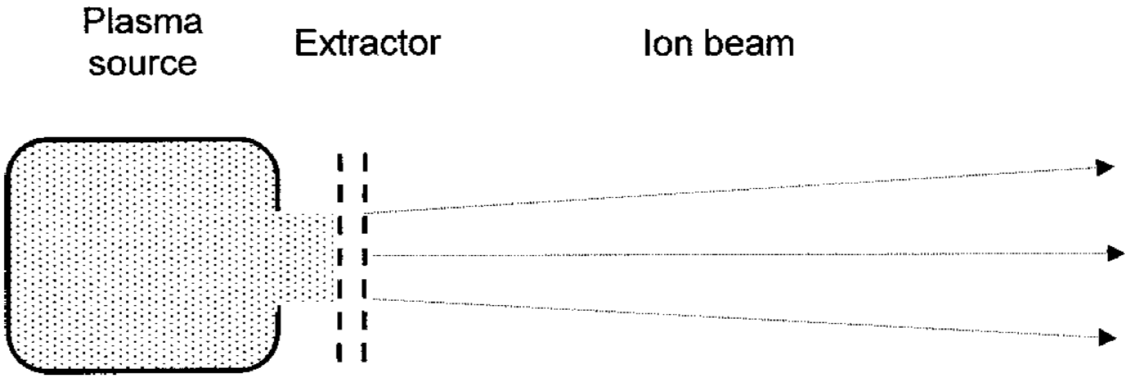
Ion source, plasma source, and plasma gun

- 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.

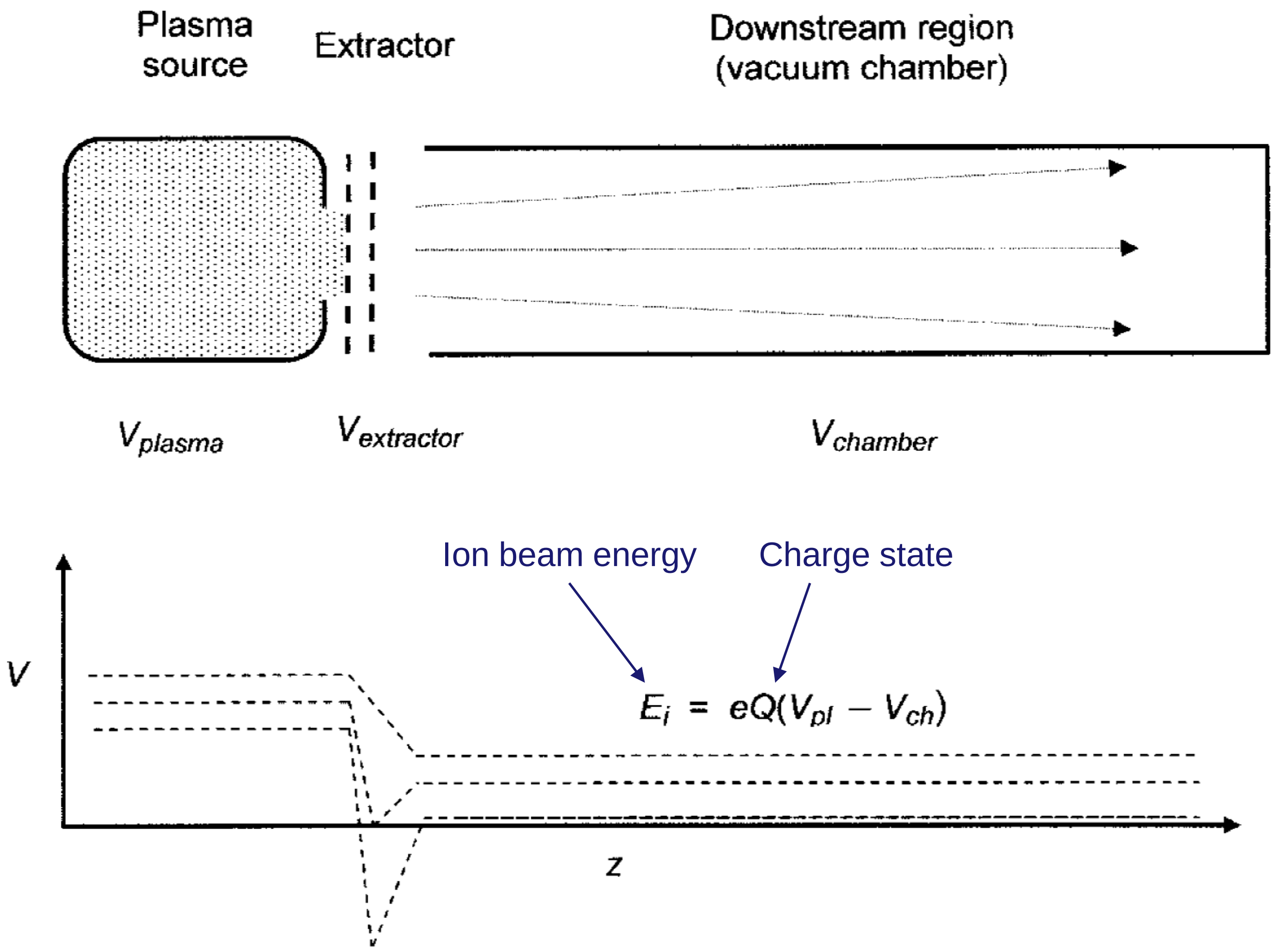
The ion source consists of a plasma source and an extractor

- 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

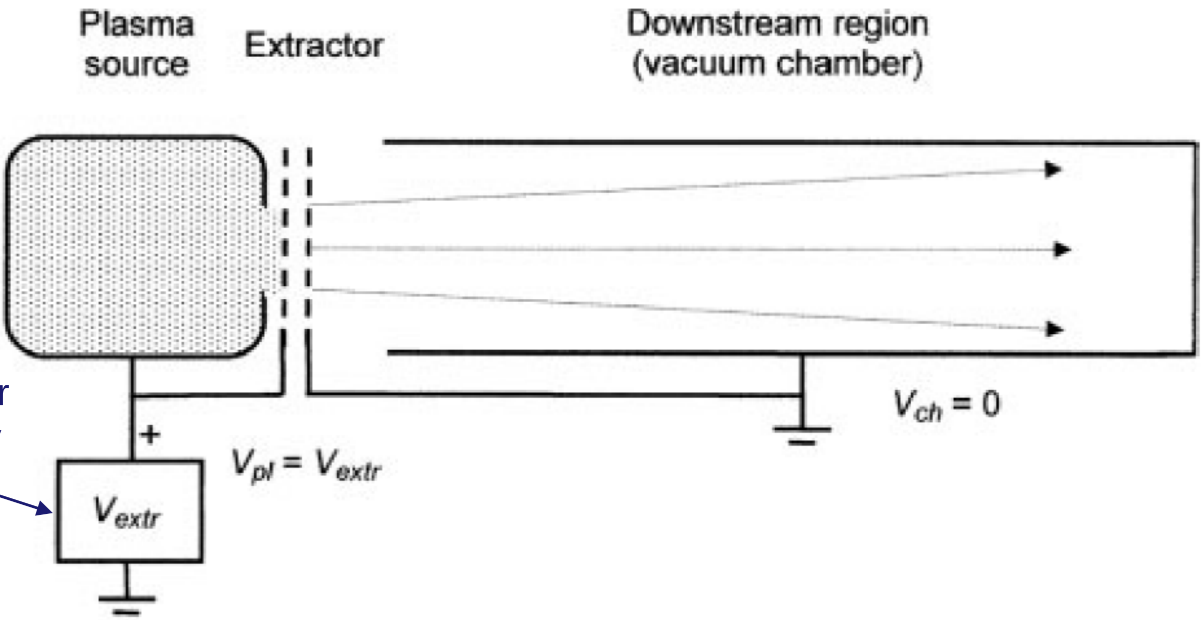


Ion beam energy

Charge state

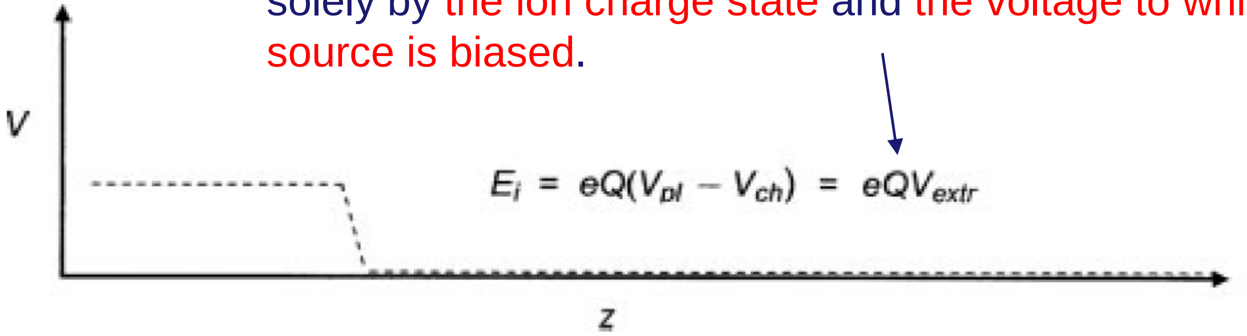
$$E_i = eQ(V_{pl} - V_{ch})$$

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



Extractor supply or accelerator supply

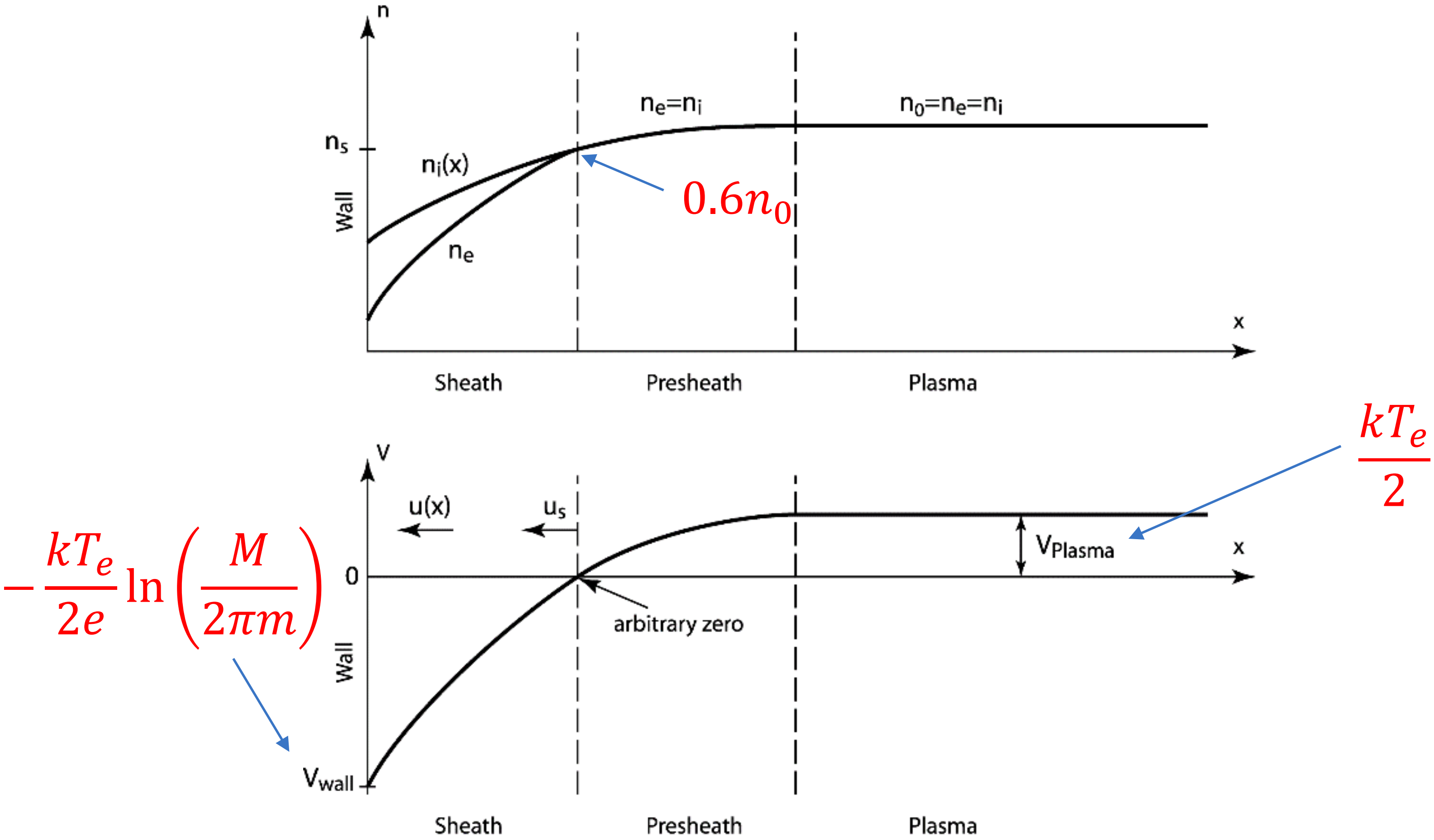
The ion beam energy (energy of the ions in the beam) is determined solely by the ion charge state and the voltage to which the plasma source is biased.



$$E_i = eQ(V_{pl} - V_{ch}) = eQV_{extr}$$

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 3kTe, and the electron temperature Te is often only a few eV.



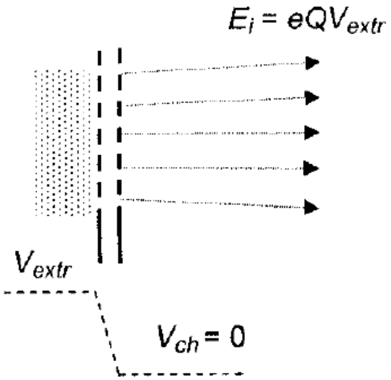
$0.6n_0$

$$\frac{kT_e}{2}$$

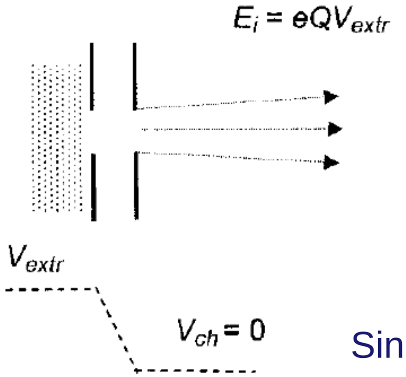
$$-\frac{kT_e}{2e}\ln\left(\frac{M}{2\pi m}\right)$$

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.



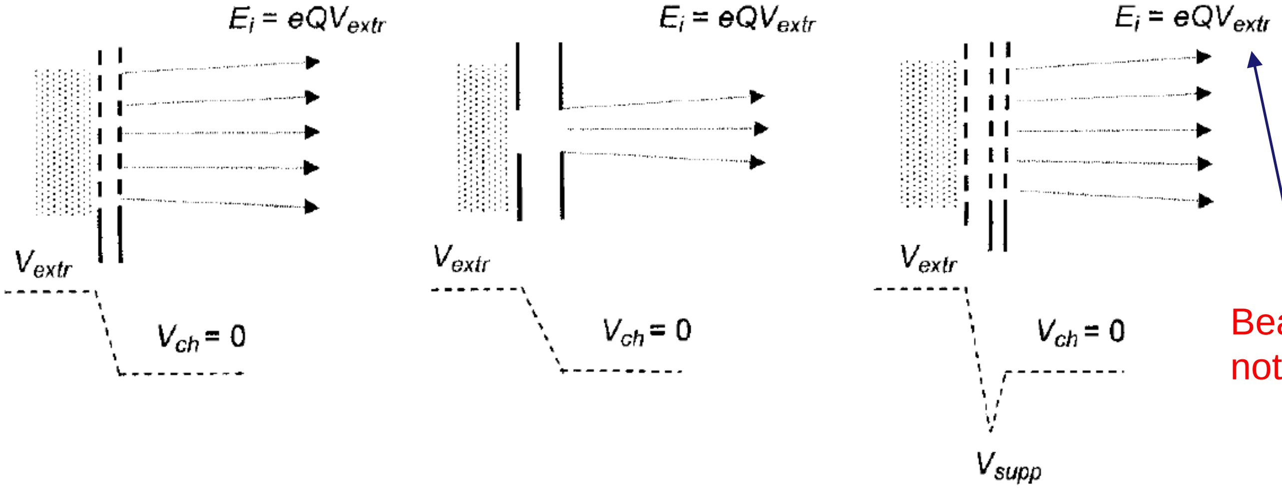
Multi-aperture



Single aperture

Ion beam formation

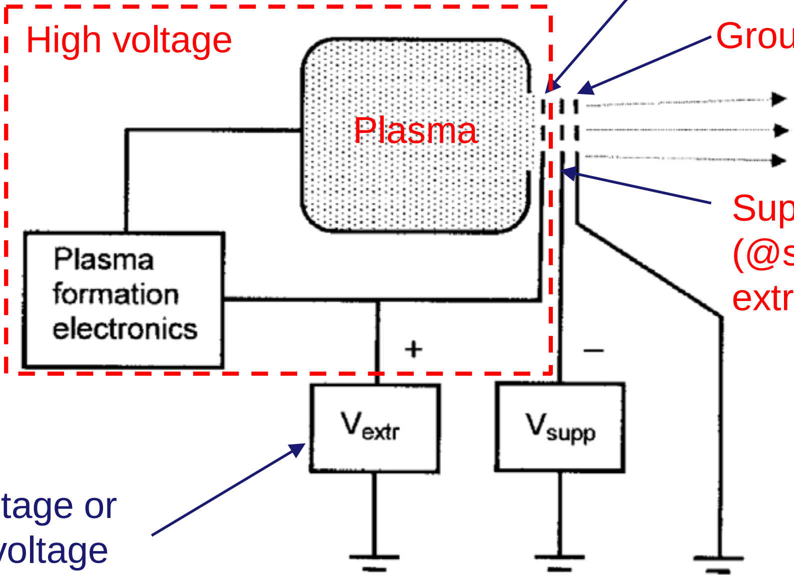
- Often a three-electrode extractor design is used, with the new electrode inserted between the plasma grid and the ground grid and biased to a relatively low negative voltage. The function of the middle grid is to inhibit the backflow of electrons into the ion source from the downstream region, and 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.



Beam energy is not changed!!

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.



Plasma electrode (@extraction voltage)

Ground electrode

Suppressor electrode (@suppressor voltage ~ 10% of the extraction voltage)

Extraction voltage or acceleration voltage

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

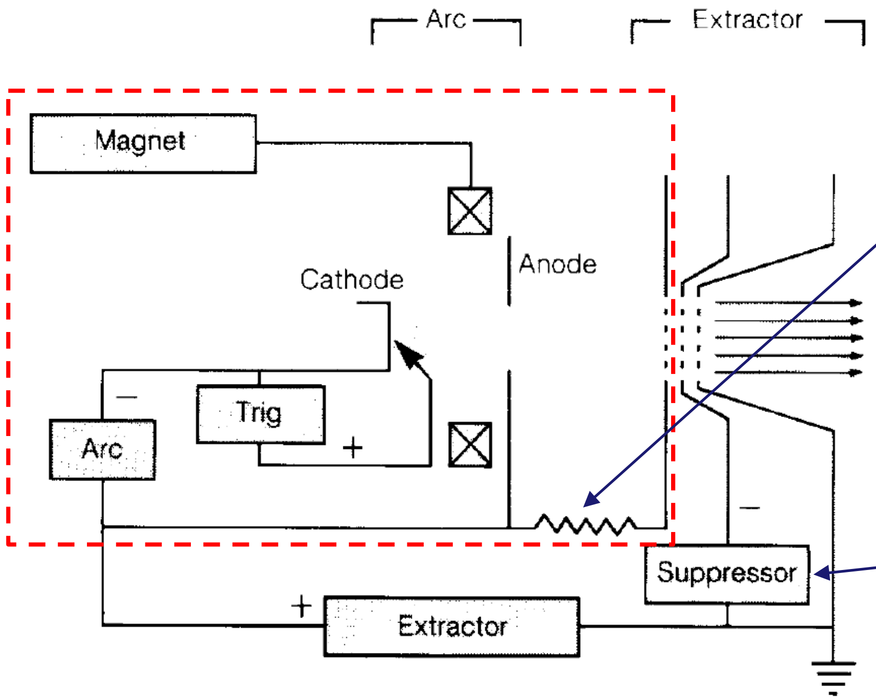
- [Beam energy] The term beam energy refers to the energy per ion in the beam, as the product of the ion charge and the extraction voltage. In a high vacuum ambient the ions propagate with no significant loss of energy by collisions with the background gas. But for higher vacuum system gas pressures, 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.



High voltage

limiting the current that can be drawn to the grid (and hence limiting arcs to the grid)

suppressing the flow of back-streaming electrons from the downstream region back into the ion source