# AN OVERVIEW OF LINAC ION SOURCES*

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*Abstract*

This paper discusses ion sources used in high-duty-factor proton and H- Linacs as well as in accelerators utilizing multi-charged heavy ions, mostly for nuclear physics applications. The included types are Electron Cyclotron Resonance (ECR) sources as well as filament and rf driven multicusp sources. The paper does not strive to attain encyclopedic character but rather to highlight major lines of development, peak performance parameters and type-specific limitations and problems of these sources. The main technical aspects being discussed are particle feed, plasma generation and ion production by discharges, and plasma confinement.


## INTRODUCTION

For the purpose of this presentation, the term Linac is narrowed down to include rf structures that accelerate ion beams with duty factors between about 5% and continuous operation. This group of Linacs includes high-current proton and H- machines as well as accelerators utilizing low- or moderate-current beams of multi-charged heavy ions, mostly for nuclear physics applications. Main types of ion sources serving these Linacs include Electron Cyclotron Resonance (ECR) sources, filament and rf driven multi-cusp sources, Penning (PIG) sources, duoplasmatrons and duopigatrons. However, the latter three source types have been in use for more than 50 years by now with more or less stagnant operational features, and for that reason they will not be discussed in the following even though they continue to produce beams for a number of Linac facilities.

This overview does not at all strive to attain encyclopedic character in terms of source varieties and performance results but rather to highlight the dominant design features, evolving performance parameters, major lines of development and general, as well as type-specific, limitations and problems. The main technical aspects being discussed are particle feeding methods, plasma generation and ion production by discharges, and plasma confinement.

## PARTICLE FEEDING METHODS

The simplest way of feeding particles into an ion source consists of letting gas flow into the discharge vessel, but sometimes a user needs to limit the overall gas flow into the subsequent Low-Energy Beam Transport (LEBT) structure of an injector and is forced to use a fast-pulsed valve, typically piezo-electrical driven [1].

The use of gaseous or liquid compounds with high-enough vapor pressure is the next best choice, with one note of caution: many of these substances contain a chemically aggressive component, and in the discharge plasma the reaction rates are typically much faster than at normal atmosphere. Erosion of source body and extraction electrodes and a significant increase of the sparking rate in the extraction system are typical consequences. A survey on this subject is given in Ref. 2; it is certainly a very good starting point to obtain information on specific feeding techniques and substance properties.

Many substances have sufficient vapor pressure at elevated temperatures to be fed into an ion source, but this option comes with its own design constraints: Once vapor of the desired pressure has been produced it should not be lost to condensation on any surface part of the conduit to the discharge vessel or that vessel itself. In other words, the oven where the solid feeding material is heated should be the coldest part of all internal ion source components. This condition suggests the installation of hot liners in the discharge vessel or even the use of dual heating elements for oven proper and conduit. A design example where the conduit is heated by the cathode filaments is given in Fig. 1. In many cases, the ion production will be much more stable when small amounts of an auxiliary gas such as argon are added into the discharge vessel.

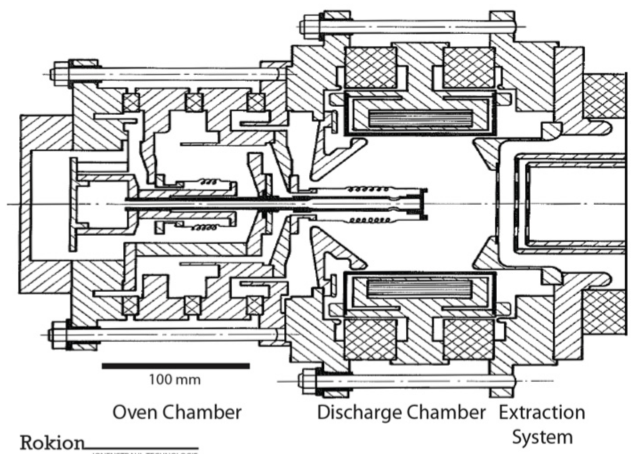


Figure 1. Hot-running multicusp ion source CHORDIS with oven and 18 cusp magnets [3]. Heat shields around the oven filaments are left out for the sake of clarity.

High-melting elements that cannot conveniently be fed into a source as part of a volatile compound can be released using the sputtering technique, adding an auxiliary gas such as argon. A dedicated sputter electrode may be inserted into the discharge vessel at a convenient location, or an existing electrode can be biased positively [3]. As with oven-equipped sources, use of sputtering benefits from the installation of hot-running liners or thinned-out electrodes to avoid re-condensation of the sputtered particles. Shares of the desired ion species typically do not exceed 10-20% of the entire extracted beam current.

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## PLASMA GENERATION

Once a material has been introduced into the ion source it has to be ionized, and usually this process is performed by striking an electrical discharge. The often used term ‘arc’ discharge is a misnomer because arcs have a negative voltage/current characteristic and are associated with rather undesirable runaway conditions. The discharge is either sustained by dc power and thermionic cathodes (filaments) or by rf power and, as mentioned above, it may be continuous (dc/ cw) or pulsed.

The applied dc or rf current and voltage values depend on one hand on the ionization requirements of the dominant feeding substance, and on the other hand on the plasma density requirements imposed by the utilized extraction system, see below.

### *Filament Sustained Discharges*

Thermionic filaments are typically made from tungsten or tantalum wire or, when using hydrogen feeding gas, from a nickel mesh covered by an earth-alkaline oxide paste. The major problem with using refractory wire material is the finite time-between-services limited by erosion of the material. For example, the LANSCE $H^-$ ion source reaches 28-35 days with an average discharge power of 500 W (12 kW peak at 4.1% duty factor), utilizing two filaments in parallel. In a study of filament data from many production runs of this ion source [4], it was found that the relative increase in filament resistance, as compared to the initial value, is a good indicator of the expected lifetime as illustrated in Fig. 2.

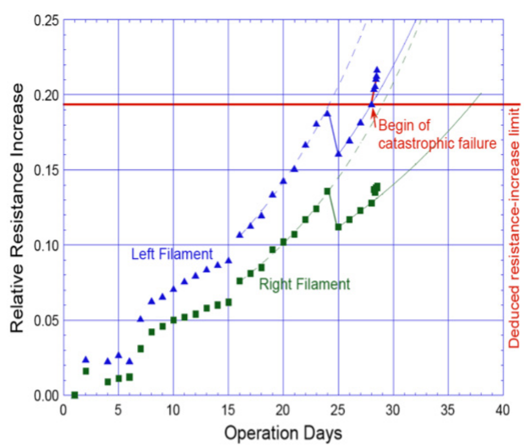


Figure 2. Resistance evolution of the two cathode filaments installed in the LANSCE $H^-$ source during a test run, showing the phases of initial shock (Days 1-7), exponential growth (Days 8-28), and catastrophic failure (left filament on Day 28). From Ref. 4.

Three distinct epochs of exponential growth are shown in Fig. 2 during Days 8-15 (less pronounced), 16-24, and 25-28; the latter two are fitted with exponential curves and extrapolated. The filament heating power values were different for each of these three phases; in fact, the close approach of the plotted data for the left filament on Day 24 led to reducing the heating power with the result that the filament lifetime could be extended by 4 more days. The catastrophic failure then occurred rapidly, once the value of 19% resistance increase had been reached.

In a theoretical and computational study of the filament failure mechanisms [5], two of the observed phenomena, i.e., exponential growth and catastrophic failure, could be well reproduced. This study proved that hot-spot formation is the dominant effect leading to excessive evaporation and failure; in addition it was found that very small diameter reductions (50 μm) of the wire can accelerate the time to failure by a factor of 2.

### *RF Sustained Discharges*

Rf sources are typically operated at 1-13.56 MHz frequency and are by design not suffering from the wear associated with hot filaments. The first aspect to take care of when driving an rf discharge is matching of the power source impedance to the plasma impedance inside the source, typically of the order of 1 Ohm. This is performed by an impedance-matching network [6]. Ignition of the discharge does not constitute a problem for filament-sustained discharges, but problems arise when rf power is utilized alone. The quick solution for the cw operation mode consists in raising the gas pressure inside the source to a level where ignition occurs at an acceptable rf power level and then reducing the pressure and possibly the rf power to their standard operating values before excessive discharge power results in damage to the vessel.

For pulsed rf operation, two ways have been successfully employed: One consists in maintaining a low-power discharge in cw mode and then applying the power pulse on top of it [7]. The two power sources need to be decoupled, for example, by choosing different rf frequencies, and the cw power source has to be protected against total reflection of its own power when the main rf pulse is applied and drastically changes the plasma impedance. This can be easily achieved by just using a cw power source with about 3 times higher nominal power rating than will actually be applied.

The other method is described in Ref. 1; it essentially consists of a spark gap that operates at significantly higher pressure than found in the discharge chamber. The gap chamber is fed with gas through the piezo-electric valve mentioned above, and a narrow opening conducts enough plasma to the discharge chamber to allow ignition of the main discharge but at the same time maintains the pressure difference between both chambers.

Rf power needs to be coupled into the discharge vessel by an antenna, and internal as well as external antennas are in use. Because of the fact that the antenna has to be shielded from the plasma by an insulating material to avoid arc-like runaway conditions, internal antennas are usually covered by single or multiple layers of porcelain, but the difference in thermal expansion coefficients of the antenna (normally copper) and the porcelain invariably leads to microscopic cracks in the porcelain, and the lifetime of these internal antennas is essentially unpredictable [8]. A rupture of the water-cooled copper tubing results in severe consequences for the vacuum system serving source and LEBT. For the same reason, water-cooled quartz tubes with inserted conductors are not offering a reliable operational solution.

An external rf antenna fulfills the operational needs much better in principle, but it requires a significant part of the discharge chamber to be made of an insulating material. $Al_2O_3$ is the most commonly used material, but for higher sustained discharge powers its thermal conductivity is insufficient, and the insulator has to be shielded from the major part of the discharge power by a slotted 'Faraday shield' [9]. Recently AlN has been employed as chamber material with an external rf antenna, and this material proved to be superior for the purpose, due to its high thermal conduction coefficient [10]. This ion source is shown in Fig. 3; recently, 100 mA $H^-$ beam current was obtained on a test stand from a 7-mm aperture at 1 ms pulse length and 60 Hz repetition rate.

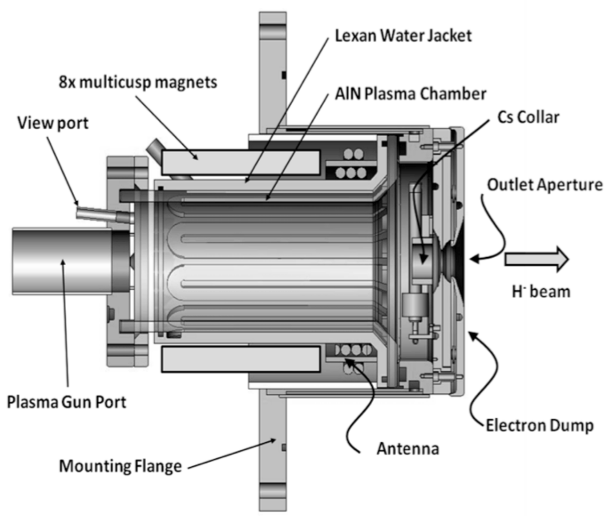


Figure 3. Developmental SNS $H^-$ rf ion source of 68 mm chamber diameter with external antenna [10]. The magnetic dipole filter (not indicated) vertically crosses the upstream end of the cesium collar.

## MULTICUSP SOURCES

Once a plasma is created, it is often convenient to restrict particle losses to the chamber walls, for the sake of power- and gas-efficiency as well as, in the case of multi-charged heavy ions, to increase the ionization probability for the plasma electrons and thus push the ion charge-state distribution to elevated values. Simple confinement of a plasma by a so-called magnetic bottle realized by two coaxial coils excited in parallel, however, leads in all rule to exciting plasma instabilities, with the undesired consequences of unstable ion beam intensity and loss of space charge-compensation in the transported beam.

Stable plasma confinement can be achieved by a minimum-B configuration where the magnetic field increases in strength with increasing distance from the center [11], and the configuration most frequently used in ion sources is the magnetic multipole, realized by lining the chamber wall(s) with either permanent magnets or electro-magnets.

These configurations generate cusped magnetic field lines, and sources with cylindrical discharge chambers and a higher number of magnets, between 10 and 20, are called multicusp or 'bucket' sources and are used to produce high-current ion beams, whereas sextupoles are most frequently used in combination with solenoid fields in ECR sources that produce highly charged beams, see below. The main effect is that only some energetic plasma particles can escape across the narrow, rectangular areas where the field lines cross a wall surface.

Examples of multi-cusp sources are shown above, in Fig. 1 (for high-current heavy-ion beams) and Fig. 3 (for high-current $H^-$ beams).

The higher the multipole number, the less do the magnetic fields penetrate towards the center of the discharge plasma, and a larger 'field-free' ($B < 10^{-3}$ T) cross sectional area allows the installation of wider extraction systems, such as the multi-aperture system depicted in Fig. 1, because the plasma density needs to be uniform across the entire outlet area.

Because of the increased collision probability for each individual electron with heavy particles, a larger discharge chamber will actually require less discharge power than a smaller one to create a plasma density value to match the applied beam extraction field [12].

The beam current I [mA] of a pure ion species with atomic weight A that can be extracted by a voltage U [kV] from a single, round outlet aperture of a multicusp source of matching plasma density is given with some margin by:

$$I = 0.5\, A^{-1/2}\, U^{3/2} \qquad (1)$$

This formula is based on a semi-empirical model that combines aberration-dominated optics effects of the beam formation process with empirical breakdown limits for the extraction gap [13]. Multi-aperture extraction systems with N apertures yield N times these values, but at the expense of a very significant emittance increase.

While the creation of positive, heavy ion beams in multicusp sources is straightforward and mostly raises issues of maximum plasma density, achievable charge-state distribution and time-between-services, hydrogen ions are somewhat more difficult to deal with. For protons and deuterons, the issue is the distribution among atomic and molecular ions ($H/D^+$ vs. $H/D_2^+$, $H/D_3^+$). The distribution cannot be pushed to enhancing the atomic ion shares by just raising the discharge voltage as one would do to get higher-charged heavy ions; instead, vibrational states of the neutral $H_2$ molecules have to be excited in greater numbers, and that requires copious low-energy electrons.

Apart from installing hot-running liners or certain insulators such as BN, the best method for enhancing atomic hydrogen ion shares consists in separating a part of the discharge chamber by a magnetic dipole filter-field from the main volume [14]. The filter keeps energetic electrons from passing into the $H/D^+$ production zone, whereas colder electrons can migrate through, due to their higher collision rates and the ExB drift effect. However, the primary plasma needs about 10 times higher electron densities than required for the extraction; hence the importance of carefully engineering the discharge chamber design with respect to high instantaneous and average power.

While negative hydrogen ion beams are transported by Linacs mainly for the purpose of utilizing charge-exchange injection into an accumulator ring, the high-duty-factor part of this group of ion sources is important enough to briefly be treated here as well.

There are two main principles of generating $H^-$ or $D^-$ ions: Volume and surface production [15]. Volume production follows similar principles as found with positive atomic ions, except that the optimum electron energy for $H^-$ creation is even lower and electrons with energies above 10 eV as well as positive ions and neutral atoms can easily destroy negative hydrogen ions once they have been formed. As a consequence, these ion sources include magnetic filters and are operated at the lowest possible neutral gas pressures.

Surface production occurs predominantly due to fast particles sputtering absorbed hydrogen atoms. For surface materials with low work function values, such as Cs-covered Mo or solid Ba, there is a fairly high probability for the released hydrogen particles to be $H^-$ or $D^-$. Two source types utilize these basic facts: Two-chamber multicusp sources as the one shown in Fig. 3 where the second chamber is made up by the walls of the cesium collar downstream of the dipole filter, and multicusp converter sources [16] that include a biased, Cs-covered converter electrode where negative ions are formed and accelerated towards the outlet electrode. A modern example of a converter source is shown in Fig. 4. To reduce the amount of electrons that are co-extracted with the $H^-$ ions, a permanent-magnet ‘repeller’ tube is installed in front of the outlet aperture.

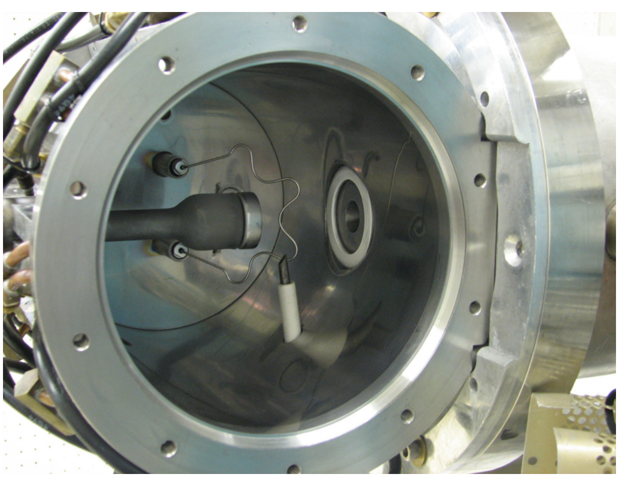

Figure 4. Multicusp converter source for $H^-$ with 192 mm inner chamber diameter. [4]. The converter electrode is at the center; cesium vapor is injected from the bottom, and the electron repeller is shown on the right, hiding the outlet aperture from view.

The peak result obtained with this ion source on a test stand from a 10-mm aperture at 0.835 ms pulse length and 60 Hz repetition rate is 24.5 mA.

## ECR ION SOURCES

ECR ion sources rely on the fact that electrons can gain substantial energies from microwave fields when their orbital motion around magnetic field lines created by two co-axial solenoids is in resonance with the microwave frequency f [17]:

$$B_{res}\ [\mathrm{T}] = 0.0354\ f\ [\mathrm{GHz}] \qquad (2)$$

When ECR discharges are operated at gas pressures around $1\times10^{-6}$ Torr the electron energy can exceed 1 keV, and at the same time recombination rates for the created ions are very low. These are optimal conditions for creating highly charged ions through step-by-step ionization processes. On the other hand, a line of ECR sources has been developed that operates around $2\times10^{-4}$ Torr, and these conditions are well suited for creating high-current beams. As with the rf driven multicusp sources, ECR sources are free from the wear associated with hot filaments, exhibit very long times-between-services and are typically operated in cw mode.

### *ECR Sources for Highly Charged Ions*

To obtain highly charged ions, one needs to minimize the operational gas pressure but also to increase the electron density in the plasma as much as possible, but there is a cut-off limit for the achievable density $n_e$ that depends on the applied microwave frequency [17]:

$$n_e\ [\mathrm{cm}^{-3}] \leq 1.25\times10^{10}\ f^2\ [\mathrm{GHz}^2] \qquad (3)$$

As a consequence, ECR sources for highly charged ions have been pushed to higher and higher microwave frequencies, and the top model VENUS [18], shown in Fig. 5, operates at 28 GHz. To satisfy Eqn. (2) for this frequency, a resonant magnetic field of 1 T (10 kG) is needed, and the peak field produced by superconducting magnets reaches 3.4 T. Modern ECR sources exhibit an asymmetric solenoid field with the higher peak being upstream of the lower peak (2.3 T for VENUS).

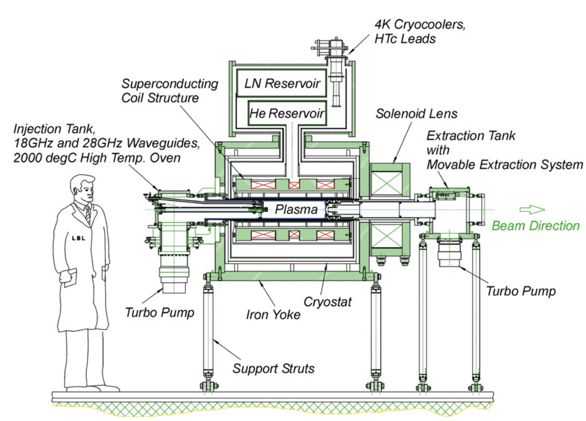


Figure 5. VENUS ECR ion source [18].

Apart from the longitudinal plasma confinement provided by the solenoids, ECR sources for highly charged ions also need a radial, minimum-B, confinement mechanism to enhance the ion persistence, and a sextupole is the most convenient choice. The needs for high magnetic fields to improve the ion confinement time (several ms are typical) contrast with the requirement for low fields near the outlet area to extract intense ion beams.

The VENUS sextupole field reaches 2.1 T at the chamber wall. Recent peak results [electrical μA] for beams created by VENUS are: $^{16}O^{6+}$- 2850; $^{16}O^{7+}$- 850; $^{129}Xe^{28+}$- 222; $^{129}Xe^{38+}$- 7; $^{238}U^{35+}$- 175; $^{238}U^{47+}$- 5; $^{238}U^{50+}$- 1.9.

The 3-d field pattern created by the superimposed magnetic systems results in a cigar-like surface where the resonance condition, Eqn. (2), is fulfilled. The width of this surface is given by the Larmor radius of the circulating electrons, and it was discovered that this width could be substantially enlarged and thereby the power efficiency of an ECR source enhanced if microwave power of a somewhat lower frequency was fed into the source in addition to the main power, essentially doubling the effective ionization volume [19]. Another method of achieving the same goal consists in utilizing a broadband, Traveling-Wave-Tube-based amplifier that puts out microwave power over a wider frequency band [20]. The group in Ref. 20 recently reported about 30% power efficiency increase due to fine-tuning of the microwave frequency favoring resonance modes on the discharge vessel axis.

A major draw back associated with advanced ECR ion sources regards the emission of x rays at increasing intensities as electron density and microwave power are raised. This feature requires adequate external shielding to protect personnel and jeopardizes the source components themselves, especially the superconducting magnets.

## *ECR Sources as Charge Breeders*

ECR sources have become the tool of choice for a very specific task: the ionization to high charge states and formation into secondary beams of radioactive particles generated in a primary beam target of so-called Rare Isotope Accelerator facilities. Main aspects of this utilization are the comparatively high particle and ionization efficiencies of ECR sources and their modular design that lends itself to minimizing activated waste [21].

Two very recent examples of ECR-bred charge states obtained by the group quoted as Ref. 21 are: $^{133}Cs^{20+}$ at 3% particle efficiency and $^{85}Rb^{15+}$ at 3.6% efficiency.

## *ECR Sources for High-Current Beams*

A special condition for the propagation of microwaves allows their penetration into an overdense plasma [22], beyond the cut-off limit described by Eqn. (3). This effect is being exploited by high-current proton sources operated at 2.45 GHz frequency. The pioneering example of this type delivers more than 120 mA of transportable beam current in cw mode with a proton fraction of 90% from an 8.6-mm outlet aperture [23]. These high-current ECR sources do not use any transverse confinement device.

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