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Ion Sources and preaccelerators

A pulsed proton current output of the order of 20 ma is being contemplated for the proposed linear accelerator with particle output energy in the Bev region.

From this it is possible to estimate approximately the required proton beam intensity in the preaccelerator.

$$I_{input} \times 0.75 \text{ (proton\%)} \times 2 \text{ (buncher)} \times \frac{75}{360} \text{ (phase acceptance)} = 20 \text{ ma.}$$

From this $I_{input} = 64$ ma.

This figure does not take into account losses in the linear accelerator and in the region from proton source to linear accelerator. If any appreciable losses would occur in the linear accelerator it would most likely occur in the particle energy region below $\cong$ 10 Mev. Therefore, in first approach, it is reasonable from experience with existing linacs to neglect beam losses after injection. From proton source to linac injection, beam losses will occur, mainly due to aberrations in the preaccelerator optics, which first of all cause a reduction of beam output of the preaccelerator compared to the ion source output (losses to focussing elements) and secondly will cause part of the beam to be unacceptable in the transverse phase space area admittance of the linac. Consequently, it seems necessary to design the proton source and preaccelerator with a total beam capability of 100 ma. pulsed current.

The subject of proton sources for a linear accelerator can be logically divided into two steps.

1) formation of protons
2) formation of a beam suitable for linac injection

Because of the magnitude of beam currents involved, space charge repelling forces in the beam, especially at lower energies, will play a dominant part in beam formation, therefore also

3) space charge problems

will be considered.

1) Formation of protons

With the advancement of particle accelerator design a great deal of attention has been given to the design of suitable ion sources, resulting in a multitude of different types and designs. In general, however, the output current capabilities, even under pulsed conditions, are in the region of a few milliamperes, possibly up to 10 ma.* Regarding the design aim of a total beam of 100 ma, it is fortunate that in recent years the state of the art** has advanced so that now three types of ion sources are available which will be able to produce or have already produced ion currents of the order of 100 ma under pulsed conditions.****

These are:
- a. rf ion source
- b. P.I.G. source
- c. duoplasmatron source

Various designs in each category are possible and have been used, however, in the following only the basic types will be considered.

Before discussing these types of ion sources separately some facts common to each of those will be covered.

1.1) In general a proton source can be simplified to a source chamber, in which ionization of the hydrogen gas takes place, with a small hole in the chamber wall through which the ionized particles are extracted. Unfortunately, neutral gas also will flow into the vacuum system through the extraction hole.***

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*Ion sources for mass separators ("calutrons") are not being considered here, as generally unsuitable for particle injection into a linac.

**This expression can be justifiably used for the subject matter on hand.

***This applies certainly to pulsed operation of the ion source, it is generally true also for dc operation, but would be less important.

****The high current ion injector as developed by Lamb and Lofgren (RSI, 27, 907, 1956) will not be discussed here; this source requires high pumping speed because of extraction area geometry. This is difficult to attain in a c.w. type pre-injector with long gradient column.

In the case of a Cockcroft-Walton type preaccelerator this generally has to be pumped through a long gradient column. This results in higher pressures near the ion source where high field gradients are desirable for beam extraction.

Further, the obtainable beam current depends, with proper extraction parameters, predominantly on the maximum attainable plasma density in the ion source. For a certain value of beam current the extraction hole size can be made smaller, with consequent less gas flow into the preaccelerator, if the plasma density is higher.

Therefore, in order to evaluate the relative merits of the three types of ion sources mentioned above, it is useful to know the operating pressure (p) for stable operation, the maximum obtainable plasma density, n_i and related to n_i the maximum current density output. Also, because part of the ionized particles in the ion source will be lost due to recombination or collection on electrodes (these factors mainly depending on the particular design of the source), another useful figure of merit is the gas efficiency $\eta_g \left(= \frac{\text{number of ionized particles out}}{\text{number of neutral particles in}} \right)$

1.2) The energy spread, Δe of the protons after extraction is in general negligible in comparison with the usual injection energy spread,* nevertheless it should be considered in connection with beam optics in the extraction region, especially in the region where extraction takes place at the plasma boundary. Therefore it is desirable to keep Δe low. In ion sources with plasma boundary extraction, i.e. where the ions diffuse through the plasma boundary instead of being forced out by applied internal fields Δe is small because the extraction field is shielded at the plasma boundary.

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*In the case of the BNL preaccelerator, the Cockcroft-Walton voltage output is 0.75 Mv with voltage variations of the order of 100 V. (= 1 part in 10^4).

1.3) Although ions with m/e values different from that of the proton will be filtered out in the linear accelerator or possibly before that by magnetic steering or focussing elements it is desirable to obtain a high proton percentage in the particle beam because ions other than protons are an unnecessary drain on the power sources and needlessly increase beam expansion due to space charge forces.

1.4) As a last figure of merit the power efficiency can be defined as

$$\eta_p = \left(\frac{\text{ion current out}}{\text{total power in}} \right)$$

For comparison of the three mentioned types of ion sources the following table is now useful.

	RF Source	P.I.G.Source	Duoplasmatron Source
p (microns)	10 - 50	20 - 100	20 - 100
n_i (ions/cm^3)	10^{10}-10^{11}	10^{10}-10^{11}	$\sim 10^{14}$
current density(A/cm^2)	≤ 1	≤ 1	up to 100
η_g	10^{-2} - 10^{-1}	10^{-2} - 10^{-1}	10^{-1} - 1
gas consumption(Ncm^3/h)	10 - 100	10 - 100	$\cong 50$
Δe (eV)	$\leq 10^2$	≤ 10	≤ 1
proton percentage (%)	60 - 90	50 - 80	60 - 90
η_p (ma/W)	10^{-3}-10^{-2}	10^{-2}-10^{-1}	10^{-2}-10^{-1}
discharge current (A)	-	$0.1 - 10^*$	$1 - 20^*$
power input (KW)	$0.1 - 10^*$	$0.05 - 5^*$	$0.1 - 2^*$
total ion current out (ma.)	$1 - 100^*$	$1 - 100^*$	$1 - 500^*$

An asterisk (*) specifically refers to pulsed operation and power input figures have to be multiplied by duty cycle.

It should be stressed that these figures are representative only and variations from the stated values are not uncommon, this depending to a great extent on operational parameters and design variations of the basic types. For example, in the P.I.G. source stable running pressure depends on discharge chamber length and for certain geometries lower pressures have been reported. Also with the duoplasmatron source, output ion currents of up to 1000 ma. have been reported. A short discussion of the individual sources follows.

1a) RF source. In its simplest form this source consists of a discharge chamber in which an rf gas discharge is excited by means of a coil around the chamber which is driven either C.W. or pulsed from an rf oscillator. In the case where a tuned coil is used around the chamber one speaks of a "magnetically" excited plasma. An alternative form is where electrodes are brought into the chamber and are fed from the rf oscillator ("electrically" excited). Usually the first form of excitation is being used. Frequencies in the range of 1 - 100 $Mc/_s$ are generally employed. Extraction of the ions takes place through a narrow cylindrical canal either by diffusion of the ions through the canal or by introducing an extra electrode in the chamber which is then given a (usually pulsed) positive potential; in this case the ions then leave the source with a higher energy. This extra electrode may be pulsed up to 40 kv and the ions leave the source with this equivalent energy. The critical region for optimum extraction is therefore in this case between extraction hole plate and plasma boundary.* To counteract recombination (recombination coefficient for metal = 1, quartz 7 10^{-4}, pyrex 2 10^{-5}) the extraction channel is covered with a ceramic or pyrex cup. This seems to give the added benefit of focussing the ions, after leaving the plasma boundary, through the extraction channel, by means of fields due to positive charges deposited on the ceramic, see diagram on following page.

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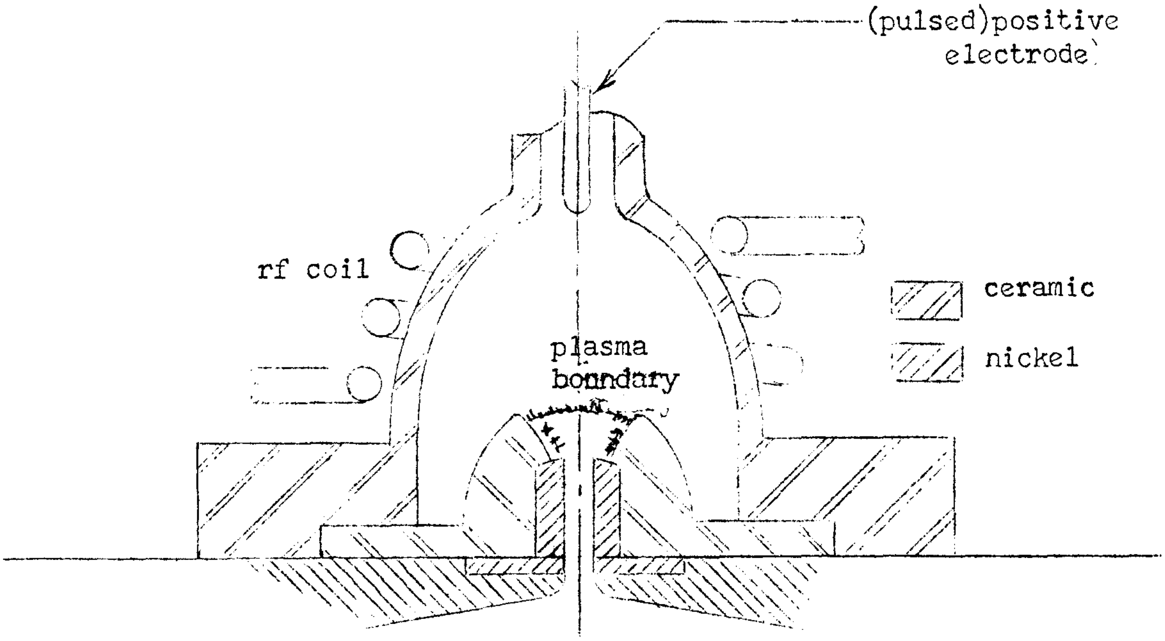
*This is different in the duoplasmatron source and P.I.G. source where the plasma boundary is essentially at zero potential during extraction, and the critical extraction region is between extraction electrode and plasma boundary.



With a clean ceramic wall high output currents have been obtained because of optimum focussing through the extraction channel. During operation a conductive layer may be deposited on the ceramic; this disturbs the potential distribution because of the impossibility of maintaining a layer of positive charges on the inside wall. Consequently the output current is reduced. For this reason regular servicing is necessary for optimum performance.

1b) P.I.G. Source. The "Penning Ionization Gauge" ion source consists in its simplest form of an cylindrical or ring anode with a cathode on either side. A magnetic field is introduced axially to increase electron path length. With a positive voltage on the anode with respect to the cathode, the familiar cascade dc discharge is excited whereby electrons lost for the ionization process are replenished by secondary emission (due to ion impact) from the cold cathodes and ions lost at the cathodes are replaced by gas ionization. The oscillating electrons between the two cathodes are constrained in the radial direction by the axial magnetic field and only slowly diffuse towards the anode. On the average γ (the effective secondary emission factor) electrons are produced per ion impact on the cathode. Whereas γ increases with the ion energy, higher operating voltages promote greater plasma densities. It has been found that an oxide layer on the cathodes reduces the work function for electron emission and consequently increases γ , resulting in lower operating voltages. Therefore aluminum is often used for the cold cathode because of its natural tendency to form an $A\ell_2 O_3$ layer on its surface.

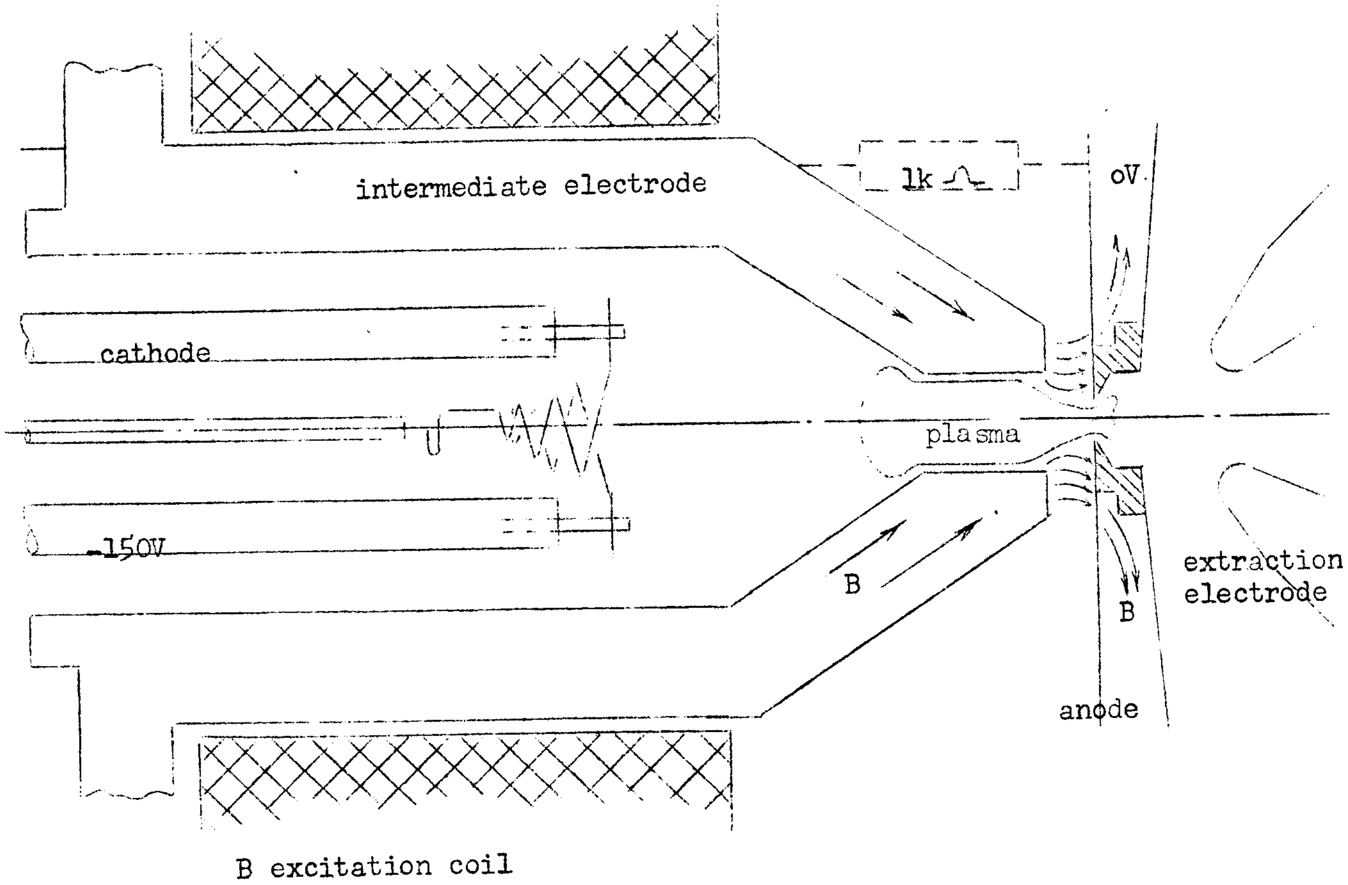
During operation the oxide layer is being destroyed due to bombardment of energetic ions. Periodic reoxidation of the cathodes is therefore necessary for optimum operation. A drawback of this type of ion source is that its steady performance is affected by the condition of the cathode. Immediately after oxidation of the cathodes performance is erratic with more pronounced tendencies for plasma oscillations, after about 200 hours of relative steady operation with high discharge currents the performance of the source tends to deteriorate again and reoxidation is necessary. Nevertheless, because of its inherent simplicity and other performance characteristics (see table on page 87) further efforts to improve this source are justified. Other types of cold cathodes have been tried, as uranium and sintered molybdenum + 10% mol. thorium oxide, with some promise of improvement, but more experimental data are necessary.

A mass spectrum of the P.I.G. source used at BNL is given below. This was taken with a mass spectrometer at the 750 kev particle energy level.

(m/e) $(m/e \text{ for the proton})^{-1}$	assignment	relative abundance
0.55	$H_3^+ \rightarrow H_1^+ + H_2$	$< 0.1\%$
0.69	$H_2^+ \rightarrow H_1^+ + H_1$	$< 0.1\%$
1	H_1^+	60.0%
2.0	H_2^+	8.5%
3.2	H_3^+	1.3%
5.1	O_{16}^{+++}	1%
7.1	(O_{16}^{++})	2.7%
16	O_{16}^{+}	22%
27	$(A\ell^+)$	3.3%
∞		$\simeq 2.2\%$

1 (c) Duoplasmatron source

A diagram of this source is shown below



The plasma region, as approximately indicated in the diagram is mainly located in the cylindrical channel of the intermediate electrode and may extend through the extraction hole. A magnetic field between anode and intermediate electrode acts as a mirror for the electrons and electron escape from the plasma is only possible close to the axis. This helps to increase the plasma density near the extraction hole. The electrons lost from the plasma are replenished by energetic (100-150 eV) electrons from a hot cathode. The electrons are accelerated through one or more plasma "double layers" in the direction of the anode. In the part of the intermediate electrode closest to the anode the mirror field becomes effective and the plasma is contracted away from the walls, which effectively decreases recombination. Also the intense ionization taking place near the axis of this region might create actually a positive potential hill due to a preponderance of slower ions over electrons. The front shape of the plasma boundary is determined by the geometry of the extraction electrodes, n_i (ion density of the plasma) and the applied extraction potential. From the source a space charge limited current is extracted determined by Poisson's equation. This has to be supplied by the maximum possible current from the plasma, which is proportional to n_i. For large values of n_i the plasma boundary will extend out of the extraction hole, so that Poisson's equation will be satisfied in the extraction region (space charge limited current). For lower values of n_i the plasma boundary will be pushed backwards until the field distribution at the boundary satisfies that for a space charge limited current. This is the reason that in both the P.I.G. source and the rf source the plasma boundary is bent inwards ($n_i \cong 10^{11}$, see table), while in the duoplasmatron source the plasma boundary may extend outside the extraction hole depending on n_i (source parameters). It is obvious that in this case high extraction voltages are necessary for good optics of the extracted beam. Low extraction voltages and high values of n_i would lead to strongly divergent beams. Any optical system for beam formation of the ion source output current should be designed with this in mind.

The extraction current obtained from this source is at least an order of magnitude larger than the space charge limited current, (as given by Langmuir's equation) indicates, if reference is made to the extraction hole area. The fallacy of this is clear and extraction of high currents do take place from a plasma boundary area which might be 10 times larger than the extraction hole area.*

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* Strictly speaking the current density figure for the duoplasmatron as given in the preceding table should be modified by this factor.

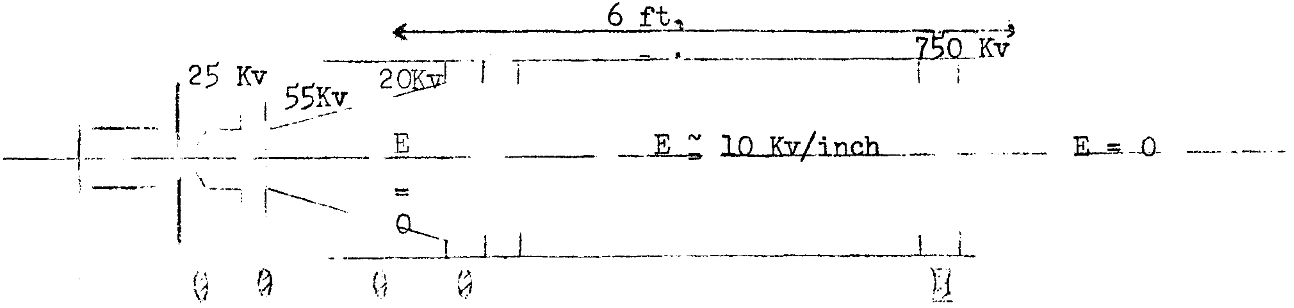
It is intended to replace the P.I.G. source of the BNL injector with a duoplasmatron ion source in the near future. Data are presently collected regarding optimum source parameters, maximum current output, proton percentage, transverse phase space area and beam optics in the extraction region as a function of the various parameters.

The duoplasmatron seems to be very suitable as a high current proton source for particle accelerators. At present its only discernable disadv antage seems to be the limited life time of the cathode.

In this respect longer cathode life might be obtained with matrix cathodes or Philips "L" cathodes. It seems even feasable to use a P.I.G. source as an electron source for the duoplasmatron,

2) Beam formation

The B.N.L. preaccelerator is schematically arranged as shown:



The light optical equivalent lenses are also indicated. Assuming now a parallel beam of a 1/2 inch diameter at a distance of 6 ft. from the high energy end, one can calculate the beam periphery back to the high energy end of the gradient column, assuming only transverse space charge forces. This is in a field free region and the differential equations can be integrated straightforwardly. The beam is then traced backwards, determining for any z value, r and $^{dr}/dz$. In the gradient column, where $E \neq 0$ the differential equations have to be numerically evaluated. The final step is to match the beam optics of the extraction region to the calculated beam optics. For the BNL injector this was done by varying the focussing voltages and the shape of the extraction electrode.

Regarding the optical characteristics of the gradient column it is necessary for high current transmission that the beam diameter at the entrance of the column be large. A limit is set by the actual diameter of the electrodes and it has been estimated from the computer results that beams of the order of 50 ma. will be close to an upper limit for this accelerator column. Larger currents will be possible but with consequent larger beam diameters at the 750 Kev end. With extra focussing elements at this location this might be still acceptable.

The case of an interrupted rather than uniform gradient column has been considered by simple matrix calculation, neglecting space charge forces, but did not seem to hold any promise of improvement. Therefore a more detailed calculation with space charge forces was omitted in this case.

The intention is to match initially the beam optics of the extraction region of the duoplasmatron source in the simplest way to the present optical system. Design studies are underway, however, to improve the present focussing system so that large beam currents can be transmitted with minimum aberrations. In this case it might be necessary also to modify the accelerator column.

3) Space charge problems

Because the space charge forces are most effective in the region of low particle energy, efforts to alleviate its influence are usually concentrated in this area.

For the BNL injector the approach has been to permit the beam to expand rapidly after extraction from the source and at the same time increase its energy in the shortest possible distance and then with a large diameter electrostatic focussing system to match it to the entrance conditions of the accelerator column (r and $^{dr}/dz$).

A disadvantage of large diameter beams in an electrostatic focusing system of given size is that aberrations might become more pronounced with a consequent loss of acceptable beam. At CERN an "einzel" lens focusing system has been designed specifically with this point in mind; i.e. to minimize aberrations.

Interesting results were recently obtained at Berkeley (LRL) with a 400 Kev experimental particle injector. A very short extraction electrode is followed by the first high voltage electrode of an "einzel" lens, in which the beam is allowed to expand and which matches the beam with entrance optics of the gradient column. Between the third "einzel" lens electrode and the entrance of the column is also a short region of high voltage gradient. Using a duoplasmatron source with this system and a solenoid focusing lens at the 400 Kev end of the column a total current of ≅ 100 ma with 90°/o protons was measured after the solenoid lens, which acted partially as a mass analyser. This was measured with a 3/4 inch aperture. In front of the solenoid (at 400 Kev) a current of the order of 150 ma. total was observed. The emittance area was also measured and found to be 11.5π

At Argonne National Laboratory experience has been obtained with a pre-accelerator based on the familiar Pierce electron optical system. In this system the potential in the beam varies with $z^{4/3}$. In this case it is required to match at the boundary the potential distribution outside the beam with the potential distribution inside the beam. This was done by using a series of electrodes of calculated shape. For beams of the order of 50 ma. this required large gradients and difficulties were encountered with sparking between the electrodes. Large currents (≅ 100 ma.) were measured with a duoplasmatron source as the ion source. However, for the preaccelerator for the 50 Mev Linac it is intended to use a modified einzel lens system as designed by A. Yokosawa.

It has been suggested to use a series of strong focusing permanent magnetic quadrupoles or electrostatic quadrupoles in the preaccelerator column. In this case it would be attractive using high, but still conservative gradients, to extract the ion beam and inject this into the gradient column. Then, with the proper quadrupole lens strength and distribution, optical properties of the beam could be shaped so that an acceptable beam is produced at the output of the gradient column.

Further ideas for counteracting the space charge problem have come forward from electron optical devices. For example, at Harwell some attempts have been made to neutralize the positive ion beam with electrons; the electrons are created by residual gas ionization and are trapped in certain regions of the beam by the use of biased electrodes.

Also in electron optics, hollow beams have been used and it would seem not an unreasonable task to construct an ion source with a ring shaped plasma and extraction system, so that only at higher energies this will be focused to a uniform filled cross-section. In a first approach it would seem that most of the approaches outlined above for obtaining higher beam intensities in a Cockcroft-Walton type pre-accelerator do also apply to a Van de Graaf injector, which has the advantage of being capable of providing particle energies of about 4 Mev, but suffers from the disadvantage of requiring longer down-times when servicing is required.