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ON THE STATE OF DEVELOPMENT OF ION SOURCES AND THE FORMATION OF ION BEAMS†

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The formation of ion beams goes back to 1886 when Goldstein did his first experiments with Kanal Strahlen. Real interest and development began with the birth of nuclear physics in 1930–33. Electromagnetic isotope separation initiated high intensity sources in the Lawrence calutrons and currents of 100 mA and more of uranium ions, at 40 keV, were already achieved before 1945. A new impetus came around 1955 when the possibility of fusion became a real challenge. The duoplasmatrons invented in German–Russian cooperation before 1960 delivered hydrogen ion currents of the order of 10 to 100 mA. Additional to this picture after 1960 came the development of ion propulsion sources for space flights and now development seems to strive for many amperes of mercury ions with kilo-electron-volt energy.

Remarkably enough a parallel line has developed since the days of J. J. Thomson and F. W. Aston (1912–1920) leading to Nier's mass spectrometer ion sources with currents from 10^{-10} to 10^{-18} A and which serve mostly analytical purposes, whereas in parallel the requirements in nuclear physics went to polarized beams of the order of 10^{-6} A of positive and negative ions.

The subject of this symposium therefore could be expected to have much diversification, as is clear from the Proceedings.(1) In this single volume sources are described requiring hundreds of kilowatts next to Dr. Heil's most elegant milliwatt ion source.

Ion source physics belongs to the most difficult branches of experimental physics. Beside the fact that deep knowledge about classical gas discharges as well as modern plasma physics is required, there is also the field of ion optics which, in the presence of space charge and magnetic fields, only can be handled with computers. Next to that there is an immense task of high temperature and anticorrosive engineering. These factors all together have led to a lot of defeatism among physicists and is the origin of the escape expression: *An ion source is a tool.* This means that if it is working and delivering the minimum beam required research is immediately stopped.

The limits are frequently dictated by the power which is available in accelerators, and very seriously in space propulsion. It is an urgent point now in fusion research how far power limitations have to be determining. Pulsed beams of many megawatts with a duration of milliseconds might lead to real fusion devices if the space-charge problem at the target side can be solved with an imploding fast electron beam.

On the low intensity side we are pretty sure that versatile ion sources for ion implantation machines have a big future. The same holds for sources for ion micro-scanning which method now seems the most sensitive way to detect impurities in surfaces by characteristic X-ray detection.

Looking at the state of the art, we see the following:

(1) *Space propulsion*: For the time being the acceleration of heavy atoms like Hg or Cs is preferred. It requires moderate dc currents of some amperes at energies of several kilo-electron volts. The total energy needed to create one ion pair is at the moment around 250 eV. The initial wide variety of ion sources has narrowed down to variations of Kaufman's PIG discharge and high frequency sources. One Kaufman Hg^+ thruster of 15 cm diam has been space-tested during five months. Space-charge neutralization in flight has been achieved. Two other thrusters are under development. One (5 cm diam) will be used for station-keeping on a Canadian communication satellite in 1974. The other (30 cm diam) will be used for final stage propulsion of solar system

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scientific missions after 1975. Cesium ion thrusters will be space tested very soon, but are perhaps somewhat less promising than mercury. The German High Frequency Hg thruster looks also promising though the required energy is still somewhat high (350 eV per ion pair against 250 in Kaufman sources). They have the advantage of having no cathode, although the latest developments in the Kaufman thruster with a hollow cathode seem very satisfactory too (13,000 hours lifetime). Material erosion is still a decisive aspect of space propulsion ion sources.

(2) *High Energy Accelerator Sources*: In 1971 all sources are of the duoplasmatron type and have roughly, while operating with hydrogen gas at pressures as high as 0.5 torr, the following parameters:

Cathode Power	75 W
Arc Current	25 A
Arc Voltage	125 V
Intermediate Electrode Voltage	50 V
Magnetic Field in Channel	2500 G
Intermediate Electrode Dimensions	5 mm diam, 10 mm length
Anode Aperture	1 mm
Intermediate Electrode–Anode Distance	5 mm

There are however big variations in the plasma expansion cup and on the ion extraction side in general. All use a high gradient Pierce field column with about 750 kV over 50 cm.

For plasma expansion cups with a diameter smaller than 20 mm a satisfactory intensity and emittance has been obtained with ion extraction voltages up to 125 kV. Currents up to 300 mA of protons are reported with an emittance area of about 1 cm · mrad. For larger plasma cups there seem to be difficulties with the quality of the ion emitting plasma cap, which is probably due to an insufficient plasma flow from the source into the cup. Scaling laws will only hold if the quality (density and temperature) of the plasma is improved. Not many oscillations in the cup plasma have been observed.

(3) *High Intensity Sources for Fusion*: These sources are passing through a fast development at the moment, there being a need for high intensity beams with small divergence of $\pm 1°$ to fit the acceptance angle of fusion devices. The classical duoplasmatron with expansion cup does not seem to give the desired beam because of too much inward bending of the plasma cap in case of high extraction voltages. The physical reason is that a very high density plasma (10^{14} to $10^{15}\ \mathrm{cm}^{-3}$) should flow through the anode orifice to equilibrate the required ion flux at the plasma cap (density $10^{12}\ \mathrm{cm}^{-3}$). It is therefore easier to have a Multi AperTure Source, called MATS, with many holes in a 10 cm extraction plate. The plasma is transported in a duoplasmatron configuration through holes in the intermediate electrode and the anode of about 1 to 2 cm diam, and then guided with a diverging magnetic field to the extraction surface. To improve the operation of the source at lower pressure and therefore lower energy input a fourth electrode has been introduced just after the normal duoplasmatron anode. It is kept at the same potential as the intermediate electrode and therefore causes a PIG discharge. We then speak of a duoPIGatron.

The extraction configuration is an accel–decel three-plate system with the last electrode on earth potential to prevent electron drain from the beam.

There are two lines to be observed in high intensity ion source development. One goes to voltages of 25 to 100 kV to get big currents thus dumping much energy into toroidal plasma (ORMAC). Currents of 10 A are reported, using proton beams. Neutralization by electron capture in a gas cell might in the future lead to a preference for D_2^+ or even D_3^+ beams. The charge exchange cross sections are higher in the latter case.

The second line goes to low energy (1 to 3 keV) high intensity beams to reach a more stable plasma in a fusion device (Baseball II) with only small deviations from a Maxwellian distribution. Also here we notice a tendency to go to molecular ion beams, with water vapor as a neutralizer ($\sigma_{\mathrm{chx}} = 10^{-15}\ \mathrm{cm}^2$). Even cluster ions are considered.

A future development of D^- ion beams of 50 to 100 keV and many amperes is desirable as the stripping of D^- is of the order of 85 per cent in gas cells. Such beams should be of the order of

10^3 A, to supply fuel for fusion reactors of about 1500 MW.

(4) *Atomic Beam Ion Sources*: The last decade has seen two orders of magnitude improvement in the polarized beam current that can be produced with a *ground* state atomic beam source. The first sources constructed, based upon the proposal of Clausnitzer, Fleischmann and Schopper, produced 0.1 μA of polarized hydrogen ions. Now 10 μA is possible as witnessed in the source for the Texas A and M cyclotron. This improvement can be attributed to the hard work that has been invested in the atomic beam system, a better understanding of supersonic flow, improved ionizer efficiencies and optimizing the sextupole design. Also in the last decade the polarization control that can be achieved is impressive and a great aid to experimental nuclear physics. The spin of a proton can be reversed by rf transitions and any direction for the spin axis is possible using spin precession devices. For deuterons six different polarization states are possible using rf transitions. The technique for injecting polarized beams into cyclotrons, tandems and linear accelerators is quite well established and good transmissions are being approached. Future developments such as a cooled discharge or crossed beam ionization will probably improve the intensity by another order of magnitude. We should also see greater utilization of polarized heavy ions, produced using the same principle.

(5) *Lamb-shift Polarized Ion Sources*: After the pioneering work by Zavoisky and by Donnally several nuclear physicists are busy developing beams with nuclear polarization using the Lamb-shift in hydrogen-like atoms. Such sources are capable of producing beam currents of positive or negative ions with large and easily varied polarizations. The method uses in essence:

(a) a positive ion source delivering a strong beam of protons or deuterons with a velocity of about 3×10^5 cm/sec (500 eV H^+);

(b) a charge exchange canal with Cs gas where an electron is attached to the positive ions. Some of these captures happen in the metastable $2^2S_{1/2}$ state;

(c) a succession of combinations of axial magnetic lenses with perpendicular electric quench fields to select some hyperfine states and retain others;

(d) an ionizer with gas (Ar or J_2) either to strip the atoms or to add an electron. So here the production of H^+ or H^- happens with a preset polarized nuclear state.

These sources are of primary importance when negative polarized beams are desired (tandems).

The beam now available on target from such sources can be as high as 0.1 μA. Application of some of the ideas reported in the Brookhaven Symposium on intense positive sources to the Lamb-shift sources lead us to think that polarized beams larger by an order of magnitude may be possible in the near future. This combined with the ease of adapting the Lamb-shift source to pulsed operation and its possible use for other hydrogen-like ions like $^3He^{++}$ make it an extremely useful tool for nuclear physics research.

(6) *Negative Ion Sources*: Finally, several activities seem to be going on in the creation of *negative ion beams*. Most interesting is that doubly charged negative ions of the halogens are reported. The most simple source of negative ions is a classical duoplasmatron with off-axis ion extraction.

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