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Recent progress in ion sources and preaccelerators

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Summary

Recent progress in ion sources is reviewed. The types of sources discussed include positive and negative proton and deuteron sources developed for conventional preaccelerators and for neutral beam applications. Positive heavy ion sources for conventional linacs and for induction linacs are included. Negative heavy ion sources are used for tandem electrostatic accelerators. Positive and negative polarized ion sources for protons and deuterons inject cyclotrons, tandems and linacs. Some recent preaccelerator designs are summarized.

Introduction

Ion source development of many different types of sources has been undertaken by groups throughout the world. Groups working on each type of source generally have good communication with each other, but it is also valuable to have interaction between research groups working on different source types. For example, the development of the multipaperture sources in the ion engine field and for neutral beams offers useful computer methods and extractor designs for high current injectors for particle physics and heavy ion fusion. The techniques developed in experimental plasma physics are also valuable for ion sources. The contact ionization sources developed in plasma studies and also for ion engines are useful for negative heavy ion sources and for high current induction linac injection. Also, the magnetic bucket confinement system for plasmas is finding applications in high current sources for neutral beam formation. So we need a healthy interaction between various source people and with those in plasma science.

The listing and description of ion sources is such a large field that it would take a book to do it justice, such as the one by Vayry. Recent reviews have been given by Osher on many light and heavy ion sources, by Curtis on duoplasmatrons, by Clark on heavy ions, by Clark and Selliger on sources for heavy ion fusion, by Haebeli and Glavish on polarized ion sources, and by Kunke1 on neutral beams for fusion. The present review will concentrate on sources developed for particle accelerators and sources developed for other fields which may have useful applications in particle accelerators. In such a large field of development, only a few typical examples can be chosen to illustrate recent developments in each source area.

Positive Light Ion Sources

Positive Sources for Accelerators

Sources for conventional linacs, summarizing by Curtis, have traditionally been duoplasmatrons producing up to 5 A of proton current with a normalized emittance after the column of .5 cm-mrad and a duty factor of 10⁻³. Recently duoplasmatrons have been developed for dc operation for several applications.

Los Alamos has tested an annular duoplasmatron which produces a 250 mA dc beam of hydrogen ions at 125 keV as a prototype for an Intense Neutron Source (INS) of tritium bombarding a deuterium gas jet. The annular design was chosen because it could produce a large area plasma, and could be easily cooled for long lifetime. The emittance was found to be large, perhaps due to the radial arc contribution to the transverse ion velocity. A Pierce column was used with 6.4 cm diameter extraction iris. The authors suggest that a cusp-field source would satisfy the requirements of simplicity, uniform plasma and low emittance, and a modified Pierce column is preferred.

Chalk River has developed a dc duoplasmatron for the Fast Intense Neutron Source (FINS) project, which will use a 25 mA, 300 keV deuterium beam on a rotating tritium-titanium target. The source uses a ceramic plasma expansion cup to reduce the emittance. Beam intensity is 44 mA of hydrogen ions at 74 kV, with 73% protons and a normalized emittance of .1 cm-mrad.

The duopigatron has also been developed for dc beams in the 100 mA range. J. Osher of the Lawrence Livermore Laboratory is developing a dc duopigatron source for 150 mA of 400 kV D+ beams to bombard a rotating tritium target for the Rotating Target Neutron Source-11 (RTNS-I1). The source is one of the MATS series, which is scaled down from a 1 A injector for the Baseball fusion experiment, shown in Fig. 1. It uses a multi-aperture (round holes) extraction system. The 3 grid plate accel-decel arrangement blocks secondary electron flow and increases extraction voltage. The beam is analyzed by a 90° magnet in the high voltage terminal to separate the D+ from molecular species. A solenoid lens then matches the beam to a large aperture (10 cm diameter), low gradient (15 kV/cm) column. Complete space charge neutralization is assumed in the terminal and in the ground transport. The per-
formance has been consistent with design expecta-
tion. The source has produced 104 mA of D\textsuperscript{+} at
22.5 keV and 87 mA of D\textsuperscript{+} on target at 300 keV.
Normalized emittance is .11 cm-mrad.

A duopigatron is being developed by Chalk River\textsuperscript{11} for a 50 keV 500 mA dc proton beam as
an injector for a 1 GeV 300 mA fissile fuel breeder
accelerator. It is based on an Oak Ridge design
with accel-decel extraction electrodes and a
multiaperture array of circular holes. Up to 450
mA total hydrogen ion current has been extracted
from the source.

The SIN group in Zurich is building a new
injector for its ring cyclotron meson factory.
The design\textsuperscript{12} calls for a 40 keV, 30 mA dc proton
source in a 860 kV terminal. The source, Fig.
2, is a scaled down version of a fusion research
design built by Culham using magnetic bucket
confinement and a 4 electrode extraction system.
Figure 3 shows the terminal, with isolation of
the source from the column as at Livermore.\textsuperscript{12}
This isolation provides separation of H\textsuperscript{+} from
molecular ions before the column, a good vacuum
in the column, beam matching and diagnostics in
the terminal. Initial source tests show 35 mA
total dc current at 40 keV.

At LASL a dc source\textsuperscript{15} is being designed for
the Fusion Materials Irradiation Test Facility (FMIT). The requirement is 125 mA of D\textsuperscript{+} at 100
keV to accelerate 100 mA of D\textsuperscript{+} to 35 MeV. The
source is based on the single aperture duopigatron
SARA designed by Osner of Livermore, which will
provide the necessary current with an excellent
normalized emittance of .02 cm-mrad. A total
ion current of 100 mA at 100 keV has been obtained.
A cusped field is being tested, based on a Culham
design.

Present Berkeley sources produce 65 A beam
currents in an extraction area of 10 x 40 cm\textsuperscript{2}
at 120 keV, with 5 sec pulses. Filament and arc
currents are each 1000 A. A recent Berkeley
source\textsuperscript{16} is shown in Figs. 5 and 6. It is cubical
in shape, 24 cm on a side. It uses hot tungsten
filaments to generate plasma, and line cusps fields
for confinement. Filaments are operated space
degree limited for stable pulsed operation. Arc
cent at 500 A and plasma density is 400 mA/cm\textsuperscript{2}
in the extraction grid. The line cusp version
achieves a fraction of 75%, compared to 65%
without cusps. Future requirements include longer
pulses of up to 30 sec, where cathode life is
a problem, so lanthanum hexaboride and oxide cath-
odes are being investigated.

At Oak Ridge a magnetic bucket confinement
system is used in the plasma expansion section
of their duopigatron source,\textsuperscript{9} Fig. 7. The buckets
dump out plasma fluctuations, spread the plasma
more uniformly over the extraction electrode and
give high atomic ion fractions, up to 80%. This
model produces 60 A at 40 kV for 300 ms pulses.

Extraction systems have been extensively
developed for these high current sources. Accel-
decel systems are used to block electrons and
increase extraction voltage. Multiaperture arrays
of either slots or round holes are used to produce
the multiaperture currents required. A Berkeley
slotted extractor\textsuperscript{9} is shown in Fig. 8. The cal-
culation of beam trajectories through this
extractor\textsuperscript{9} for 120 keV is shown in Fig. 9. It
uses a computer code which integrates the trajectory
calculation in the presence of space charge to
obtain electrode shapes giving minimum beam diver-
gence. The first electrode has a Pierce shape
for initial electrostatic focusing. A fourth
electrode is added to a 3 electrode, 20 keV
extraction column, to give 120 keV.

Positive Heavy Ion Sources

Present Sources

In present positive heavy ion accelerators
such as linacs and cyclotrons, the principal source
used is the Penning Ion Gauge (PIG) type. Since
these sources have been reviewed previously,\textsuperscript{5}
only brief mention of them will be made here.
They produce microamp to milliamp beams of all
elements with charge states up to about Xe\textsuperscript{7+}
at duty factors up to 100%. Since they are still
the best high intensity source of heavy ions,
they will be used in several new heavy ion
accelerators such as the new SuperHILAC injector
at Berkeley, the superconducting cyclotrons at
Michigan State University and the GANIL cyclotrons
in France. Active development programs are under-
way at these labs.

At the UNILAC in West Germany extensive
development has been done on the duoplasmatron\textsuperscript{5}
for heavy ions at high duty factors of 30-100%.
Great improvements were made in its high charge
state output, but it did not equal the PIG at
the high charge states and for solid material
feed reliability. The duoplasmatron has been
tested at several other labs\textsuperscript{5,6} for low duty factor
operation with low charge states.

The Hughes Research Labs have developed a
high brightness Penning source\textsuperscript{7} for 30 mA of
Xe\textsuperscript{7+} using a single extraction aperture, and 100
mA with multiapertures. It is shown in Fig. 10.
It uses a diverging magnetic field of tens of
gauss and permanent magnets around the outside.
The extractor has a Pierce geometry. It will be
used with the Argonne National Lab 1.5 MV acceler-
cator column for ion beam fusion injector develop-
ment.\textsuperscript{18} A calculation of beam trajectories in
this column, including space charge, is shown
in Fig. 11. This 3 gap configuration would
accelerate 100 mA of Xe\textsuperscript{7+} to 1.5 MeV.
magnet removes electrons and matches the beam to the column. The source has produced 50 mA of H\(^+\) from the 750 kV column, and is the principal injector at Fermilab.

At Los Alamos a Penning source of the Novosibirsk type has been developed, shown in Fig. 20. It has given 108 mA at 18 kV through a 90° bending magnet.

**Negative Heavy Ion Sources**

Negative heavy ions are widely used in tandem electrostatic accelerators. They are produced by direct extraction, charge exchange from a positive beam, head-on collision of a positive beam with a vapor, and by sputtering from a solid surface with a positive beam.

One of the most useful designs is that of Middleton, shown in Fig. 21. A cesium beam from surface ionization is accelerated and focused to bombard a sputter cone of the desired material. Negative ions are sputtered out and accelerated into the downstream lens system. A desired ion can be quickly selected from an array of cones of different materials, making this a very versatile source.

A recent negative heavy ion source was developed at Wisconsin. The source is shown schematically in Fig. 22. It uses the filament design from the Hill-Nelson source and a sputter cathode of the desired material like the Aarhus source. Cesium vapor is added. The negative ions from the cathode are focused toward the extraction aperture. The source produces beams of good intensity and brightness. Middleton is testing a similar source, but without the magnetic field.

**Polarized Ion Sources**

Polarized hydrogen or deuterium ions are produced in an atomic beam source by separating spin components of an atomic beam in a multipole magnet and then ionizing the beam, and in the Lamb shift source by selective quenching of the 2S metastable state and charge exchange in vapor or gas.

Recent improvements have been made in the atomic beam source by ANAC, Inc. In Fig. 23 is shown the new atomic beam system with the dissociator closer to the first sextupole, four independent short sextupoles instead of one or two long ones, and better pumping along the beam.

Improvements have also been made in the electron beam ionizer by ANAC, as shown in Fig. 24. The solenoid is split into 6 parts to produce an optimum magnetic field, which normally is higher on the ends than in the center. Power supplies and mechanical rigidity have been improved to stabilize the operating point. The beam currents resulting from these improvements in the atomic beam and ionizer have increased from 10 \(\mu\)A to 60 \(\mu\)A cw and 100 \(\mu\)A pulsed.

Recent advances have been made in negative ion polarized beams from an atomic beam source. Haebeli's group at Wisconsin has used a colliding beam method of fast Cs\(^0\) with polarized thermal H\(^0\), Fig. 25. The Cs\(^0\) donates an electron to the H\(^0\) by charge exchange. A current of 3 A, a polarized H\(^-\) was obtained, larger than is available from present sources. Further improvement is expected.

An even more promising development for negative ions is the use of colliding beams of fast D\(^-\) with thermal polarized H\(^0\), proposed by Haebeli. High intensity D\(^-\) beams are available and the cross-section is higher than for Cs\(^0\). Figure 26 shows a possible arrangement for this scheme. The main problem is space charge blow-up of the newly formed polarized H\(^-\) by the fast D\(^-\) beam. This can be controlled by using a strong solenoid magnet and by injecting a neutralizing positive beam as shown in Fig. 26, although neutralization would also be supplied by residual gas. A colliding beam experiment is underway at Argonne using this reaction, Fig. 27, which uses a small interaction region to reduce the space charge problem with a pulsed H\(^-\) beam of \(\pm\)A or more.

Sources of other polarized ions have also been built, such as \(^3\)He, \(^6\)Li, \(^7\)Li and \(^23\)Na, and some of these have been used on accelerators.

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**References**


Fig. 1. Osher's MATS III source.

Fig. 2. Culham source built for new SIN injector.
Fig. 3. 860 kV terminal for new SIN injector.
1) ion source, 2) turbopump, 3) - 9) beam transport, 10) chopper, 11) buncher, 12) accelerating column.

Fig. 4. Typical neutral beam line for magnetic fusion.

Fig. 5. Plasma region of new line cusp source for neutral beams at LBL.

Fig. 6. Section of Fig. 5 showing line cusp fields.
Fig. 7. ORNL 22 cm duopigatron with magnetic buckets.

Fig. 8. LBL 120 keV, 65A source, showing extraction slot plates.

Fig. 9. Computer designed 4 electrode extractor system for 120 kV at LBL.

Fig. 10. Hughes Research Labs Penning Source for Xe⁺.

Fig. 11. Argonne 1.5 MV accelerating column for heavy ion fusion.
Fig. 12. LBL multiaperture Xe$^{1+}$ source.

Fig. 13. Geller's SuperMAFIOS-B ECR source at Grenoble.

Fig. 14. MicroMAFIOS compact ECR source at Grenoble.

Fig. 15. Orsay CRYEBIS. Polarized atomic beam enters from left through hole in cathode. Ion beam is extracted on right.

Fig. 16. Electron gun for Orsay EBIS.
Fig. 17. LBL 1 A cesium contact ionization source and pulsed drift tube linac.

Fig. 18. Fermilab H⁺ magnetron source.

Fig. 19. Fermilab high voltage terminal with analyzing magnet for H⁻ source.

Fig. 20. Los Alamos Penning Source for H⁻.

Fig. 21. Middleton sputter source for negative heavy ions. Cesium beam enters from left. Ion beam is extracted from right.
Fig. 22. Wisconsin axial plasma sputter source for negative heavy ions.

Fig. 23. ANAC new polarized atomic beam system.

Fig. 24. ANAC improved ionizer for polarized atomic beam.

Fig. 25. Experiment at Wisconsin which produced 3uA of H⁺ polarized beam by charge exchange with fast cesium beam.

Fig. 26. Proposed system for producing high intensity polarized H⁺ beam by charge exchange with fast D⁻ beam.
Fig. 27. A system for producing high intensity polarized \( \text{H}^- \) beam by charge exchange with fast \( \text{D}^- \) beam.