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 multiaperture 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, a healthy interaction between various source people, with those in plasma science, is needed.

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 Valyi.[1] Recent reviews have been given by Osher[2] on many light and heavy ion sources, by Curtis[3] on duoplasmatrons for proton linacs, by Middleton[4] on negative heavy ion sources, by Clark[5] on heavy ion sources, by Clark and Seliger[6] on sources for heavy ion fusion, by Haeberli[7] and Glavish[8] on polarized ion sources, and by Kunkel[9] 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, summarized by Curtis,[3] have traditionally been duoplasmatrons producing up to 0.5A of proton current, with a normalized emittance after the column of 0.5π cm-mrad, at a duty factor of 10^{-3}. Recently, duoplasmatrons have been developed for dc operation for several applications.

Los Alamos has tested an annular duoplasmatron[10] which produces a 250-mA dc beam of hydrogen ions at 125 keV, as a prototype for the 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 a 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[11] 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 0.1π 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-keV D^+ beams to bombard a rotating tritium target for the Rotating Target Neutron Source-II (RTNS-II).[12] The source is one of the MATS series, which is scaled down from a 1 A injector[13] 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-

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formance has been consistent with design expectation. The source has produced 104 mA of D^+ at 22.5 keV and 87 mA of D^+ on target at 300 keV. Normalized emittance is 0.1 π cm-mrad.

A duopigatron is being developed by Chalk River[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 using a multi-aperture 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[14] 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 at 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.[12] This isolation provides separation of H^+ from molecular ions before the column, 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[15] is being designed for the Fusion Materials Irradiation Test Facility (FMIT). The requirement is 125 mA of D^+ at 100 keV, to accelerate 100 mA of D^+ to 35 MeV. The source is based on the single aperture duopigatron, SARA designed by Osher of Livermore, which will provide the necessary current with an excellent normalized emittance of 0.02π cm-mrad. A total ion current of 100 mA at 100 keV has been obtained. A cusp field is being tested, based on a Culham design.

High current sources for neutral beams

The use of multiampere neutral hydrogen beams has proven very successful in heating plasmas for magnetic fusion experiments.[9] A neutral beam injection line[9] is shown in Fig. 4. The first component in the system is a multiampere positive ion source. The development of sources for these systems has provided many useful ideas for accelerator sources.

Present Berkeley sources produce 65-A beam currents in an extraction area of 10 x 40 cm^2 at 120 keV, with 5-sec pulses. Filament and arc currents are each 1000 A. A recent Berkeley source[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-cusp fields for confinement. Filaments are operated space charge limited for stable pulsed operation. Arc current is 500 A and plasma density is 400 mA/cm^2 at the extraction grid. The line-cusp version gives higher D^+ 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 cathodes are being investigated.

At Oak Ridge a magnetic bucket confinement system is used in the plasma expansion section of their duopigatron source,[9] (Fig. 7). The buckets damp 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 multiampere currents required. A Berkeley slotted extractor[9] is shown in Fig. 8. The calculation of beam trajectories through this extractor[9] for 120 keV is shown in Fig. 9. It uses a computer code which iterates the trajectory calculation in the presence of space charge to obtain electrode shapes giving minimum beam divergence. The first electrode has a Pierce shape for initial electrostatic focusing. A fourth electrode is added to a 3-electrode, 20-keV extractor, 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,[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^{12+}, 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 underway at these labs.

At the UNILAC in West Germany, extensive development has been done on the duoplasmatron[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[5,6] for low duty factor operation with low charge states.

The Hughes Research Labs have developed a high brightness Penning source[17] for 30 mA of Xe^{1+} 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 accelerating column for ion beam fusion injector development.[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^{1+} to 1.5 MeV.

A source for 60 mA of Xe^{1+} was built at Berkeley.[19] It is shown in Fig. 12. It is based on the original Berkeley hot filament plasma generator of Ehlers[20] and the multiaperture extraction system of Osher[12] using a round hole array in an accel-decel geometry. A 30-mA beam at 22 keV was transported 1 meter with a magnetic quadrupole triplet, and the normalized emittance was 0.03π cm-mrad. The beam was almost completely space charge neutralized by residual gas. Currents up to 60 mA have been measured through a 500-kV accelerating column.

Advanced high charge state heavy ion sources

If a source could produce charge states twice as high as the PIG, the energy from a cyclotron would be four times higher, and linacs could be designed with half the present length for a given energy. Progress has been made toward this goal in the past few years.[5]

The Electron Cyclotron Resonance (ECR) source has shown great promise in this area. The most advanced version,[21] called SuperMAFIOS B, is shown in Fig. 13. It is a two stage plasma device. Plasma is created in the first stage at high pressure (10^{-3} Torr) by microwave power at the electron cyclotron resonance frequency. It diffuses to the second stage at better vacuum (10^{-7} Torr), where high charge states are created by a second microwave system. Mirror and sextupole magnetic fields confine the plasma in the second stage. Operating power is 3 MW. Charge states such as N^{7+}, Ar^{12+} and Xe^{26+} have been observed at 10^{12}-10^{10} per second intensities, much higher than those of a PIG. Much interest has developed in this type of source, particularly in Europe. A small version, MicroMAFIOS,[21] has just begun operation at Grenoble. It is shown in Fig. 14. It uses a simpler single microwave frequency system and a permanent magnet sextupole to save power. ECR sources are being built at cyclotrons in Louvain, Belgium,[22] and Karlsruhe, Germany.[23]

The Electron Beam Ion Source (EBIS) is another advanced high charge state source with promising results. This source was pioneered by Donets at Dubna[24] and later developed by other groups. The CRYEBIS[25] source at Orsay, France is shown schematically in Fig. 15. An electron gun injects beam into a series of drift tubes in a superconducting solenoid magnet, where it ionizes a pulse of gas. The ions are confined radially by the electron beam and axially by potential barriers at the end drift tubes. When the high charge states have been built up, a voltage ramp is put on the drift tubes to extract the ions. The Orsay electron gun is shown in Fig. 16. The electron beam is compressed electrostatically and magnetically. Charge states of up to Kr^{34+} and Xe^{44+} have been reported. The accumulation time of only 5 ms is much shorter than expected, likely due to reduced electron beam diameter from neutralization. This means that high repetition rates could be used and duty factors of about 50% could be obtained by storing and extracting for equal times. Average beam currents would be comparable to those of ECR sources, and higher for the heavier ions. The duty factor is ideally matched to a synchrotron. CRYEBIS will be installed on the Saturne II synchrotron in France. An EBIS has also been used on a synchrotron at Dubna.[24] The CRYEBIS will also be used to ionize a polarized atomic hydrogen beam entering through a hole in the cathode. It will be a very high efficiency ionizer compared to those mentioned in the later section on "Polarized Ion Sources."

Other methods of producing high charge state heavy ions, such as lasers and exploding wires, have very low duty factors. The use of a 300-500-keV proton beam, instead of an electron beam, in a modification of the EBIS called the PROBIS has been suggested.[26] The motivation is that the ionization cross-sections are higher. However, the radial electrostatic confinement disappears with protons, leaving only magnetic confinement.

Large area contact ionization source

One of the principal candidates for heavy ion fusion applications is a linear induction accelerator. This accelerator can accelerate large beam currents (amperes) of singly charged heavy ions starting at a few MeV. At Berkeley, a Cs^{1+} contact ionization source of 1 ampere has been developed[27] for this application. This type of source was chosen because of its high brightness (less transverse velocities than a plasma source), > 99% singly charged ions, and its high mass (uranium may be possible). The source and pulsed drift tube preaccelerator are shown in Fig. 17. Cesium vapor is sprayed onto the 30-cm diameter hot iridium anode. The space-charge limited beam is extracted by the pulsed anode voltage. The extracted current follows the predicted $V^{3/2}$ Childs' Law up to 1 ampere at 500 kV, with 4 μsec pulses. One drift tube is now operating to give 1 ampere at 1 MeV, and 3 drift tubes are expected to be in operation in late 1979.

Negative Light Ion Sources

There is a need for H^- sources for injection into synchrotrons by stripping, for injection into LAMPF, and for neutral beam magnetic fusion injectors at higher energies. Development has been done at Brookhaven, Fermilab and Los Alamos in the U.S., using designs from the Novosibirsk group in Russia.

Fermilab has developed a magnetron H^- source[28] from a design of Brookhaven. It is shown in Fig. 18. The H^- is formed by the E X B discharge in the thin annulus between cathode and anode. Cesium is added to increase the H^- production and the source is run at 350°C to prevent condensation. High ion current densities of several amperes/cm^2 are created at the extraction gap. The source, analyzing magnet and accelerating column are shown in Fig. 19. The 90° analyzing 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,[29] shown in Fig. 20. It has given 108 mA at 18kV through a 90° bending magnet.

Negative Heavy Ion Sources

Negative heavy ions are widely used in tandem electrostatic accelerators. They are produced[4] 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,[4] 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 negative heavy ion source was recently developed at Wisconsin.[30] 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[7] in an atomic beam source by separating spin components of the 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.[8] Figure 23 shows 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 by ANAC[8] have also been made in the electron beam ionizer, 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 μA to 60 μA dc and 100 μA pulsed.

Recent advances have been made in negative ion polarized beams from an atomic beam source. Haeberli's group at Wisconsin[7] 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-μA 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 Haeberli. 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[7] using this reaction, (Fig. 27), which uses a small interaction region to reduce the space charge problem with a pulsed H^- beam of 1A or more.

Sources of other polarized ions[7] have also been built, such as ^3He, ^6Li, ^7Li and ^{23}Na, and some of these have been used on accelerators.

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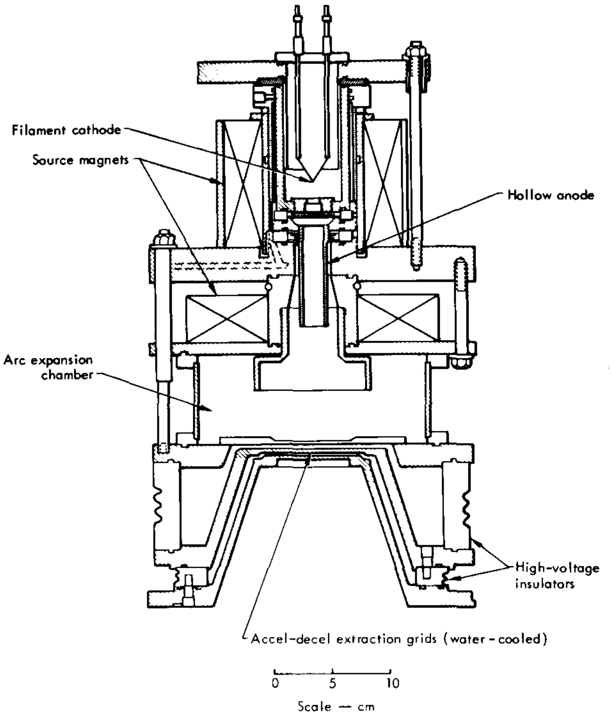


Fig. 1 Osher's MATS III source.

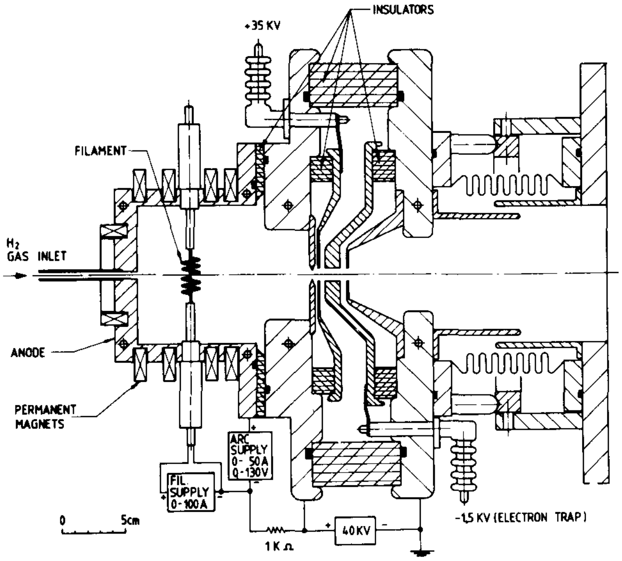


Fig. 2 Culham source built for new SIN injector.

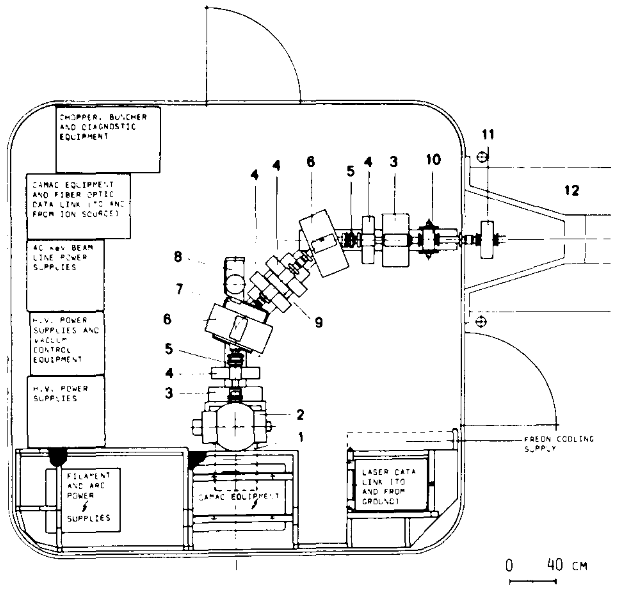


Fig. 3 860-kV terminal for new SIN injector. 1) ion source, 2) turbopump, 3) - 9) beam transport, 10) chopper, 11) buncher, 12) accelerating column.

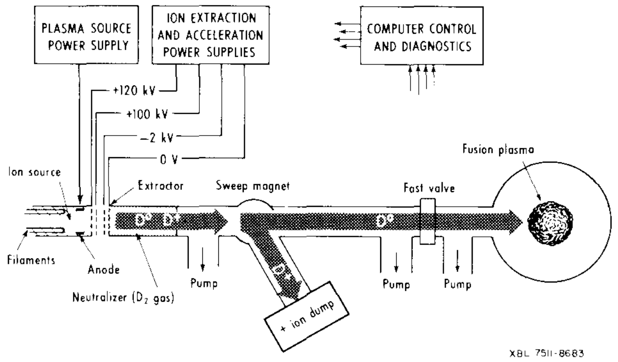


Fig. 4 Typical neutral beam line for magnetic fusion.

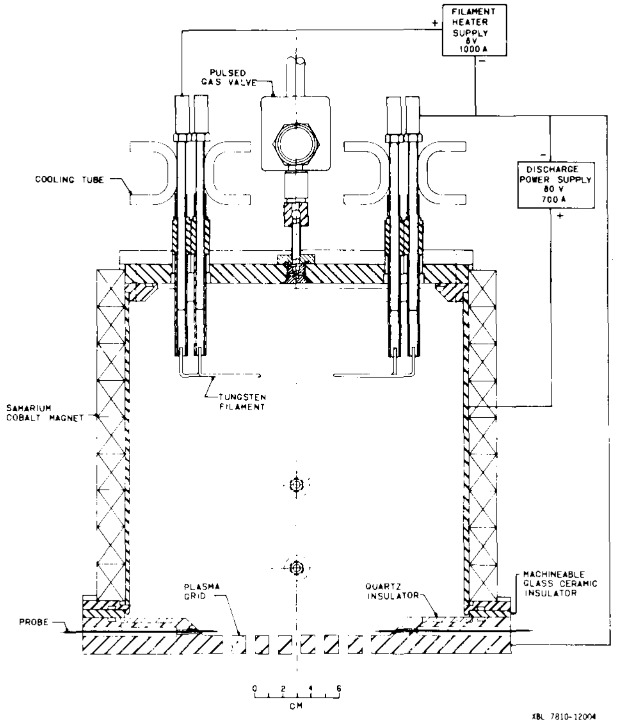
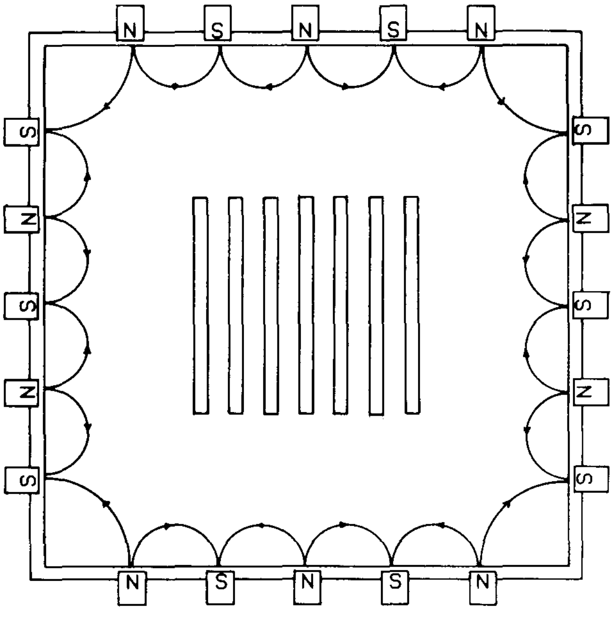


Fig. 5 Plasma region of new line cusp source for neutral beams at LBL.



(B)

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Fig. 6 Section of Fig. 5 showing line-cusp fields.

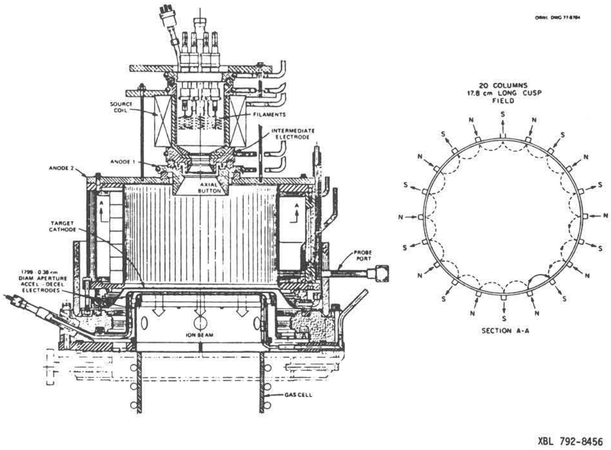


Fig. 7 ORNL 22-cm duopigatron with magnetic buckets.

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

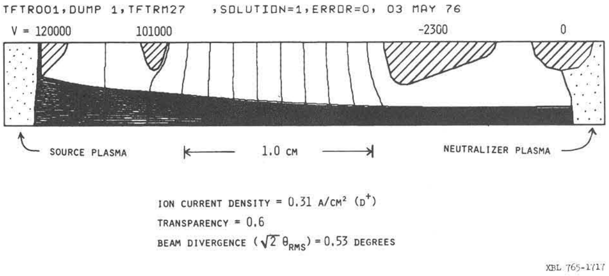


Fig. 9 Computer designed 4-electrode extractor system for 120 kV at LBL.

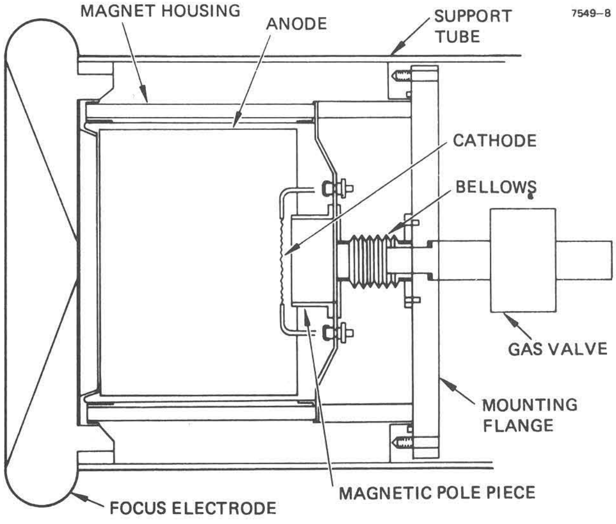
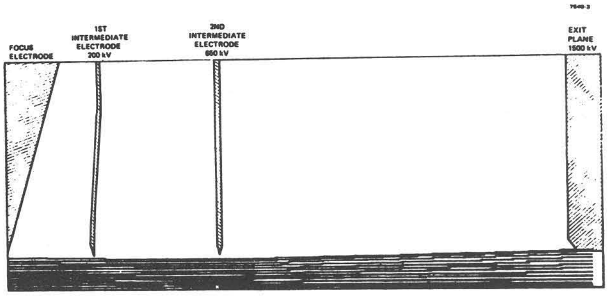


Fig. 10 Hughes Research Labs Penning Source for Xe^{1+}.



Ion trajectories for 100 mA of Xe^+

Fig 11. Argonne 1.5-MV accelerating column for heavy ion fusion.

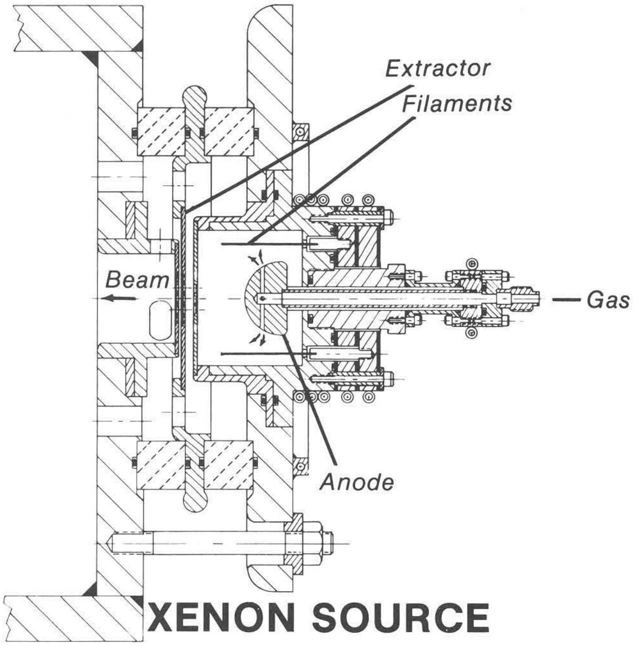


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Fig. 12 LBL multiaperture Xe^{1+} source.

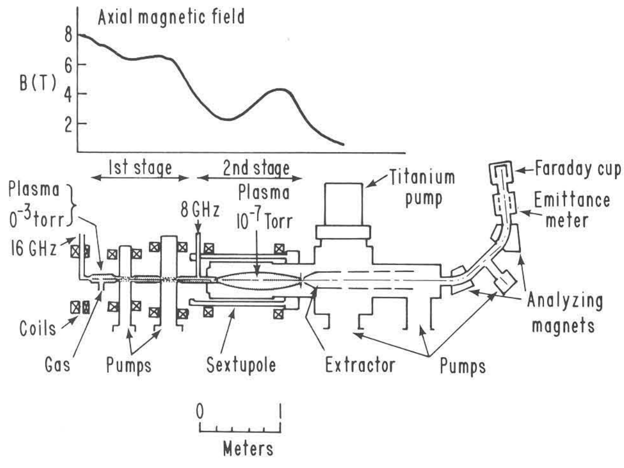

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Fig. 13 Geller's SuperMAFIOS-B ECR source at Grenoble.

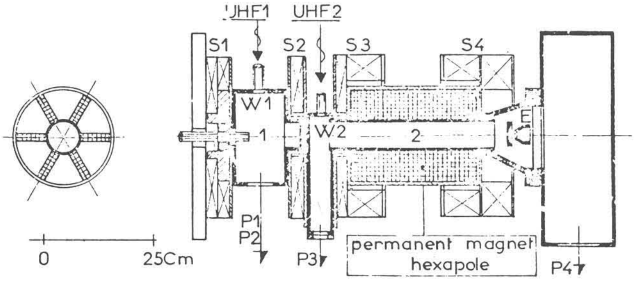

Fig. 14 MicroMAFIOS compact ECR source at Grenoble.

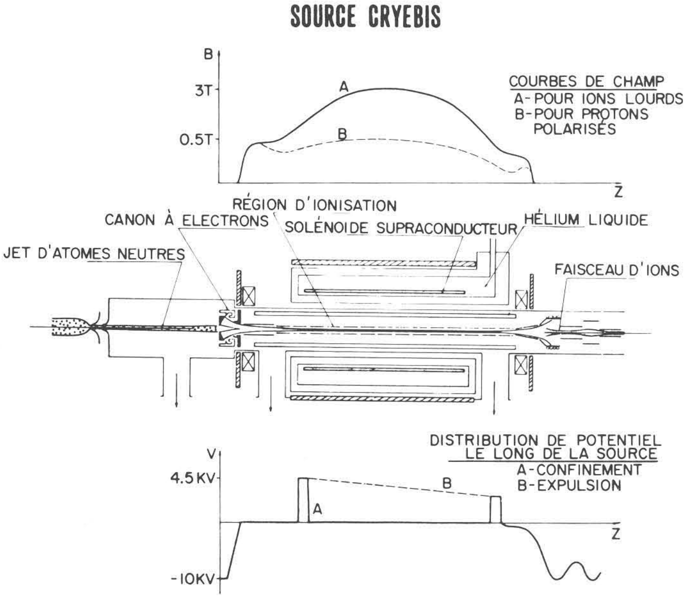

Fig. 15 Orsay CRYEBIS. Polarized atomic beam enters from left through hole in cathode. Ion beam is extracted on right.

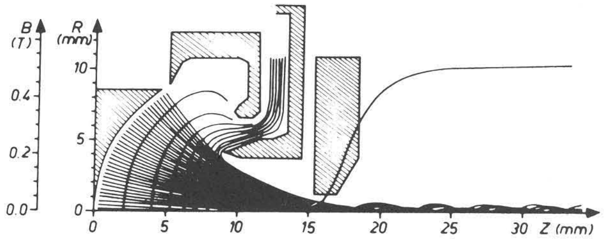

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Fig. 16 Electron gun for Orsay EBIS.

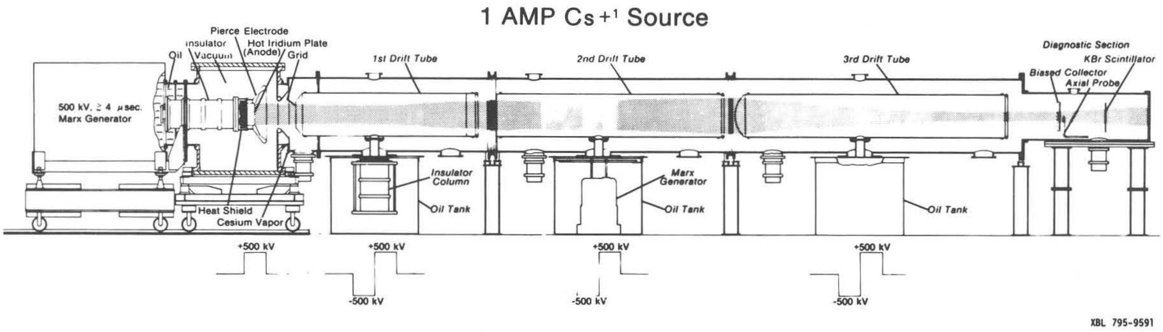


Fig. 17 LBL 1 A cesium contact ionization source and pulsed drift-tube linac.

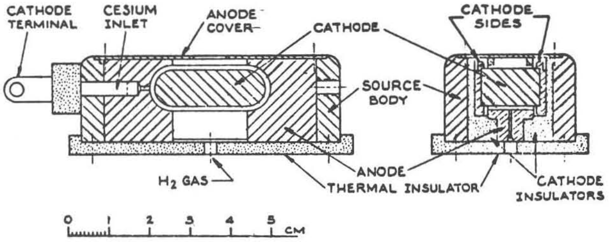
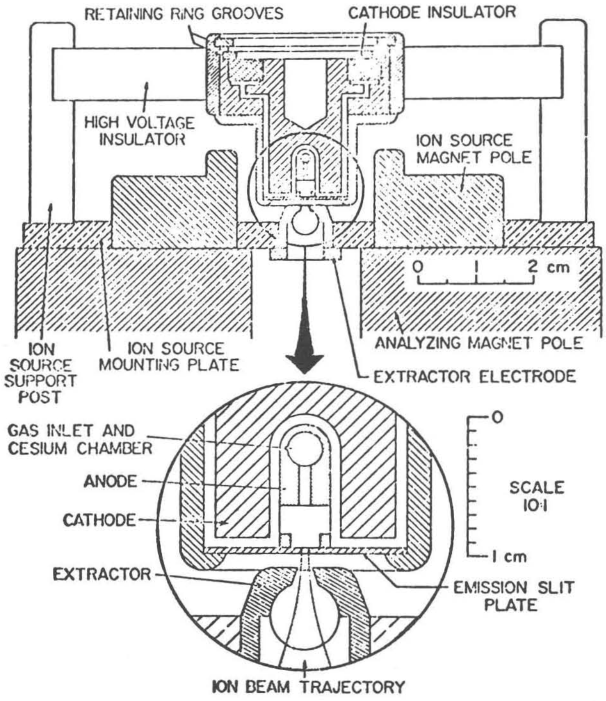


Fig. 18 Fermilab H⁻ magnetron source.



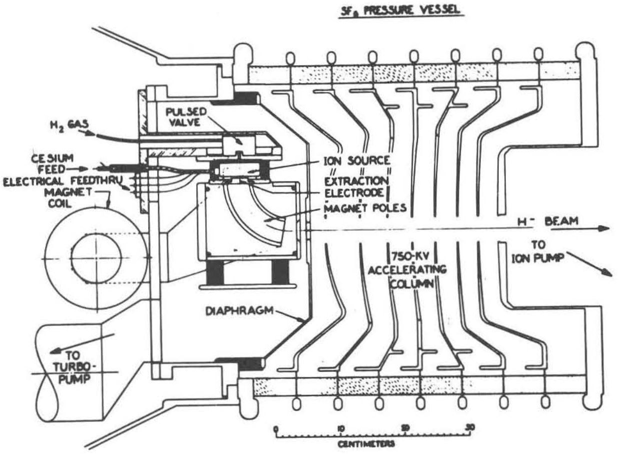


Fig. 20 Los Alamos Penning Source for H⁻.

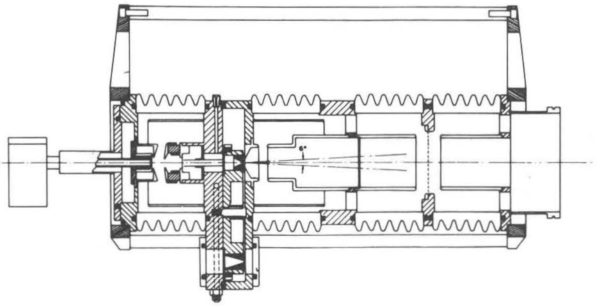


Fig. 19 Fermilab high voltage terminal with analyzing magnet for H⁻ source.

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

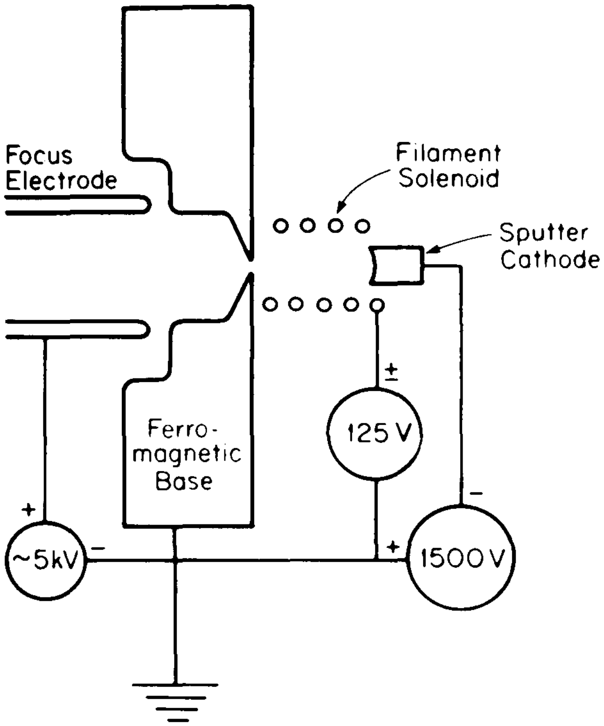


Fig. 22 Wisconsin axial plasma sputter source for negative heavy ions.

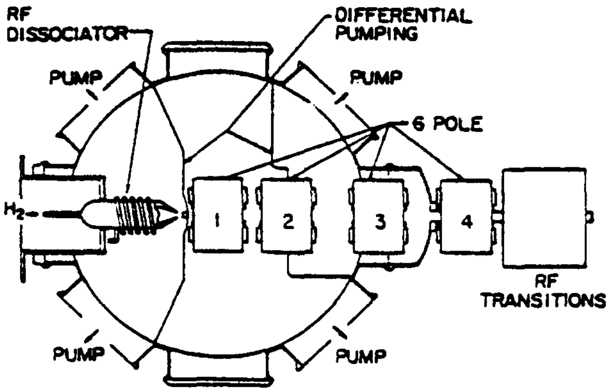


Fig. 23 ANAC new polarized atomic beam system.

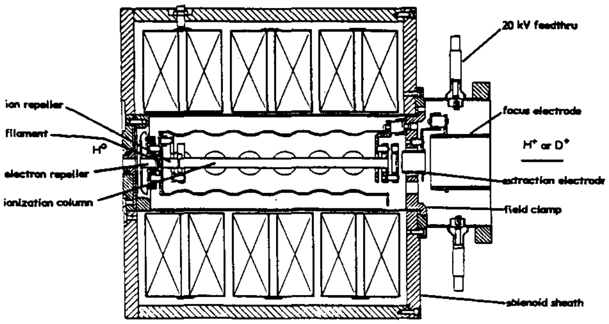


Fig. 24 ANAC improved ionizer for polarized atomic beam.

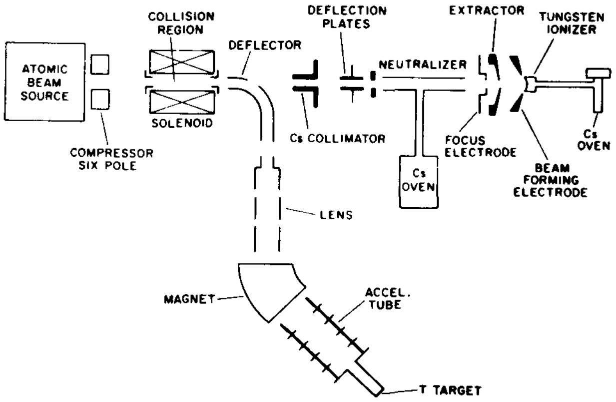


Fig. 25 Experiment at Wisconsin which produced 3μA of H^- polarized beam by charge exchange with fast cesium beam.

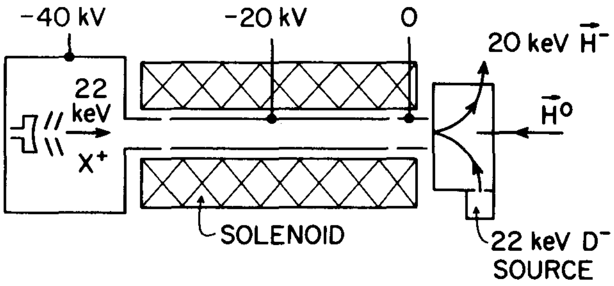


Fig. 26 Proposed system for producing high intensity polarized H^- beam by charge exchange with fast D^- beam.

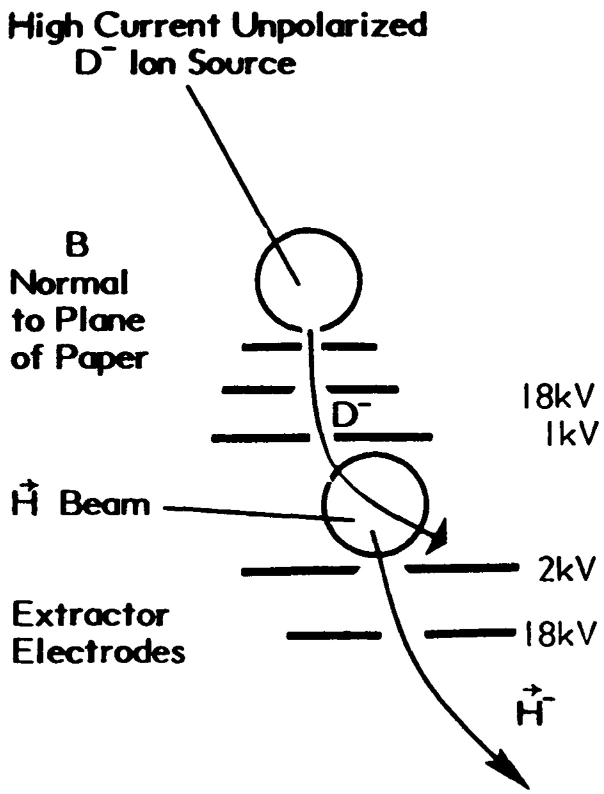


Fig. 27 Argonne system for producing high intensity polarized H$^-$ beam by charge exchange with fast D$^-$ beam.

Discussion

Hepburn, AECL: Does the Wolf computer code iterate the plasma surface shape?

Clark: I'm not positive about that.

Halbach, LBL: It does iterate on the meniscus - it finds the shape that gives a self-consistent solution.

Blewett, BNL: It was not clear to me in your pictures of polarized ion sources, where the polarization takes place. Most of the pictures seemed to show only components that are axially symmetrical.

Clark: The polarization takes place in the sextapole magnets, by separating the electron spins - they align either parallel to the field or perpendicular to the field - so in the sextupole one component is defocused and one component is focused due to the sextupole gradient. After that there is an rf transistion.

Blewett: I think the problem was that I didn't see them.

Clark: They were in the first viewgraphs. I may have not made that clear. These are the sextupoles here - "6 poles" - this is a standard component of the source. It is symmetric except for the "6 poles".

Blewett: This component appears by assumption in all of your other pictures.

Clark: Yes, this item, the sextapoles, are used in every atomic beam type of source and the colliding beams have that as a first stage.

Meads, Brobeck: Would you say something about reliability of some of these sources?

Clark: Well, that varies tremendously from one source to another. Some sources will run for weeks or months. The negative heavy ion sources can run for weeks. Some of the PIG sources run for 3 hours and then they have to be changed. Some of them run for a day: 8-12 hours. That's probably the complete range. At the 88 Inch, we sometimes change the source every 3 hours for difficult ions and run up to weeks with dueplasmatrons at low duty factor. But everybody wants to get better reliability.