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RECENT PROGRESS IN ION SOURCES†

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Summary

This paper is intended to survey recent developments in ion sources, particularly work reported at the "Symposium on Ion Sources and the Formation of Ion Beams" held in Berkeley in October 1974. The approach here will be to subdivide this topic into three main areas; briefly list and discuss notable progress in each; and finally add some additional detail through a few specific, selected examples. The major items of progress discussed include development of large-area plasma surfaces for multiple-aperture ion sources, a significant increase in available negative-ion current densities, and improved general agreement between extraction electrode design and performance.

Introduction

In recent years, there has been a fairly dramatic upsurge of interest in ion sources. In particular, the need for intense neutral beams for controlled fusion research, the evident applications of negative ions to the formation of higher-energy neutral beams and to accelerator injection, and the new field of use of highly charged heavy ions in nuclear studies have led to fairly dramatic ion source performance gains. This progress is the result of many factors, including both new ideas and the scale-up of older principles.

For discussion purposes, this paper is divided into three major subsections: general ion source features, specific ion sources, and new types of ion/plasma sources. The general ion source features are discussed in terms of the plasma source, the extraction electrode system, and the beam transport system. Because the presentation here is necessarily brief, the reader is referred for details to the Symposium Proceedings[1] noted above and to other recently published references, including those by Gabovitch[2] and Green.[3] Also, only limited coverage of highly charged heavy-ion sources and polarized-ion sources will be included here because these are topics of other invited papers in the conference program.

General Ion Source Features

The Plasma Source

The plasma source in a classical ion source performs the very basic function of supplying the ion flux over the desired extraction electrode area. As such, the requirements for an ideal plasma source might include:

1) The density and surface area of ions necessary to support the desired extraction current,
2) A high (desired) ion species fraction,
3) A spatially uniform (or at least controllable) density over the extraction area,
4) A minimum level of density fluctuations,
5) A low ion temperature,
6) High gas efficiency, and
7) High power efficiency.

Because some of these requirements tend to be very difficult to attain, if not incompatible, in practice those features most important to the specific plasma source application are optimized. The result is a diversity of specialized ion sources, each with certain distinct advantages. The plasma source appears to be the most critical component in these various ion sources. Major progress has occurred in the general areas discussed below; nonetheless, much remains to be done.

The Density and Extraction Area of Ions. The major advance in positive ion sources has come because of an increase of the plasma area available for extraction. Local extraction current densities in the A/cm^2 range had previously been available in the relatively small-area (typically <1 cm^2) primary plasma tongue of duoplasmatrons. Recent work with the LBL ($B \sim 0$) plasma sources,[4] duopigatrons,[5,6] and a radial Penning source,[7] has led to scaled plasma areas of up to several hundred cm^2 at extraction current densities of ~0.5 A/cm^2. This allows ion beam applications requiring many amperes total current — up from typically a few hundred mA a few years ago.

The major advance for H^- (and heavy negative ion) sources also comes under this heading as a dramatic increase in extractable negative ion flux density. Recent work by Dimov[8] with Cs-"treated" W cathode surfaces has produced pulsed H^- yields of up to 3.7 A/cm^2 in small ion magnetron sources. This is to be compared to previous H^- yields of typically $\lesssim$20 mA/cm^2.

The Control of the Ion Species. Work in this area shows little progress except perhaps in the case of Cs-treated surfaces for negative ions. In general, the species fractions involve details of the electron energy distribution, ionization cross sections of the material, ion containment properties, and often surface effects. At equilibrium, relative concentrations of various ion species can be predicted from the Saha equation. However, as discussed for heavy ions by Winter,[9] the ion loss rates are typically enough to significantly disturb the equilibrium values and to require solution of the coupled rate equations for the competing species. Clearly, the detailed, charged-state density distribution is a difficult problem for heavy ions where many charged states are simultaneously present.

Plasma Uniformity. Plasma spatial uniformity (or at least control) is very important to extraction beam optics and low emittance. Fortunately, the spatial uniformity for the new large-area sources is good, with $\partial n/n \lesssim 5\%$ attained for the $B \sim 0$ sources.[4]

The Ion Temperature and Fluctuations. The total transverse ion velocity from whatever cause[10] contributes to a minimum intrinsic divergence $\theta \sim \sqrt{T_i/W}$, where T_i is the total effective ion temperature, and W the extraction energy. The effective ion temperature can include contributions from dissociation (if it is from a molecular parent gas), from arc-voltage-derived sheath and volume electric fields, and from any hashy instability structure. Fortunately, the LBL ($B \sim 0$) source[4] is quiet and shows a relatively low 1.25-eV

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ion temperature. Unfortunately, low applied voltages and a reduced hash often imply low ionization efficiency, which in turn yields reduced gas and power efficiencies.

The review paper by Lejeune[11] gives a detailed listing of the various sources of fluctuations observed in various arc plasmas (e.g., flute, ion sound, and drift wave instabilities at low frequencies; and micro-instabilities usually involving the ion gyro frequency at higher frequency). The successful matching of a plasma source to an extraction system depends upon attaining the design ion density at the plasma meniscus. Variations in density either in space or time then lead to a deterioration in ion source extraction optics. Fluctuations can also lead to enhanced space-charge divergence losses during ion beam transport. The topic of oscillation suppression is relatively complex and in need of additional work. The relatively high densities of background neutrals and the proximity of conducting surfaces in an ion source should tend to simplify this problem.

High Gas and Power Efficiency. The relatively open structure of the large-area ion sources has tended to reduce the gas efficiency to 20-50%. Similarly, the low ion containment times of the B ~ 0 sources give a relatively low power efficiency of $\eta = I_{arc} V_{arc}/I_{(extracted)} \sim 4$ keV/ion.

The review paper by Green[12] describes a number of detailed models for describing many physical features of the PIG and reflex-arc-type plasma sources. However, much of the variation in character of an ion source is still attributable to little-understood factors, leaving much work to be done. For example, the diagnostics of an intense-multiple-species plasma are very difficult, particularly within the confines of the typical ion source. Langmuir probes have been very useful insofar as they have been applied, but further studies (e.g., detailed electric-field profiles) could also be useful.

Table I briefly lists selected highlights of several plasma source types to illustrate the range of development.

The Extraction Electrode System

The extraction electrodes in a classical ion source perform the function of ion beam formation and at least preliminary acceleration and electrostatic focusing. Substantial progress has been made in the three general areas described below:

1) Mechanical design of multiple-aperture systems,
2) Optimization of extraction performance, and
3) Staged electrode systems.

The Mechanical Design. The electrode design overall diameter, and cooling method largely restrict the choice of material and set a minimum for the electrode thickness. Recent electrode developments include tests of several H_2O-cooled Cu designs,[19] heat capacity limited use of Mo or W,[29] and W-coated C.[30] An additional factor, particularly for pulsed-ion sources, is the selection of material and conditioning of electrodes for maximum voltage stand-off. Semashko et al.[31] have reduced extraction electrode conditioning time by adding special steps of chemical etching, chemical clean-

Table I. Plasma Sources of Interest

Type	Use/Features — Progress	Reference
Duoplasmatron	Accelerator/high H^+ fraction; gas efficiency	Sluyters et al.[13]
	Heavy ion yield; moderate charge states	Illgen et al.[14]
	Multiple channel	Nunogaki et al.[15]
Penning	Accelerator/good H_2^+ fraction	Hooper et al.[16]
(Calutrons)	Heavy ion yield; high charge states	Bennett et al.[17]
	Radial annulus type	Semashko et al.[7]
Duopigatron	Accelerator/large area	Green et al.[12]
(Reflex-arc)	CTR/larger area; high output	Morgan et al.[18]
	Steady-state version	Osher et al.[19]
	Annular form; scalable area	Fumelli et al.[6]
B ~ 0 type	CTR/large scalable area; low $\partial n/n$, low hash	Ehlers et al.[4]
	Multipole surface e-containment	MacKenzie et al.[20]
	Accelerator/negative ion via charge exchange	Dimov et al.[21]
ECR	CTR and heavy ion, low T_i	Geller et al.[22]
e-Beam	Heavy ion, low T_i	Donets et al.[23]
Beam plasma	Low T_i	Takagi et al.[24]
		Demirkhanov et al.[25]
Surface effect	Heavy ions	Middleton et al.[26]
(Cs on surface)	Negative ion yield	Dimov et al.[8]
	Heavy negative ions	Sluyters et al.[27]
		Smith et al.[28]

ing, and vacuum bakeout to the usual part cleaning before use.

The Electrical Design and Optimization. A number of studies[32,33] have been reported, including a limited optimization of the extraction electrode geometry in three electrode accelerator-decelerator systems. In one of the most recent and general of these experimental parameter studies for circular apertures, Coupland et al.[33] provide several simple requirements for optimized performance. For example, they suggest an aperture diameter $\gtrsim 2$ times the electrode thickness and a minimum gap d $\gtrsim 1.25$ times the aperture diameter; the gap d being subject to mechanical tolerance limitations for small gaps at low voltages and to the breakdown voltage [V(breakdown - kV) $\approx 60\ d(\mathrm{cm})^{1/2}$] at higher voltages. The use of computer codes for aperture design and optimization includes studies by Bate,[34] Boers,[35] Cooper et al.[36] and Kulygin.[37] The code studies by Cooper et al.[36] and Kulygin et al.[37] particularly concentrate on slit-aperture systems as being easiest to fabricate and easiest to cool, and as having high (to 70%) transparency.

Recent progress in extraction optics design from analytical models and the above computer calculations now show good general agreement with experimental observations. Remaining differences, at least down to divergences of ~1° are believed due to experimental limitations in forming the simplified plasma meniscus model assumed for the calculations. Model corrections are normally included for the expected mixture of ion species fractions (e.g., $\sum_{i=1-3} j_i \sqrt{A_i} = K\,V^{3/2}/d^2$ for the Childs-Langmuir limited current for H^+, H_2^+, and H_3^+ ions), but usually ignore possible differences in density distributions of the charge states.

The success in achieving beams with good optics allows either the additional feature of shaping the electrode surface of a multiple-aperture electrode structure or the use of programmed inter-electrode aperture or slot pattern displacements to achieve net beam focusing (as discussed for specific sources below). Recent work for large area space-thruster steering by aperture displacement is reported by Poeschel et al.[38]

Staged-Electrode Systems. The use of electrode staging to improve ion source performance at energies either $\lesssim$keV or $\gtrsim$35 keV is a relatively new application. Cooper et al.[36] have proposed a 5-electrode system for low voltages that is designed to maintain higher voltage extraction properties while retaining good optics. Higher brightness sources at low energy would be very useful to polarized ion source experiments.[39] Similarly, both LBL[40] and Culham[41] are testing staged, high-voltage extraction systems to retain the higher current densities possible with extraction near ~20 keV; since the distance d for voltage standoff varies as V^2 the space-charge-limited current $j = K_2 V^{3/2}/d^2$ tends to be reduced at higher voltages.

Beam Transport

This subject has received the least recent attention. The major reason is simply that many ion source applications include charge exchange of the ions for neutral beam production, thereby eliminating or at least markedly reducing this problem. In particular, all of the intense, pulsed-ion sources for CTR now include prompt charge exchange in H_2 immediately beyond the final extraction electrode. Although this in turn leads to some new problems of electrode bombardment by plasma formed by inter-electrode ionization and to gas streaming problems, it is nonetheless a relatively practical solution for pulsed applications at least.

However, for applications requiring use of the primary ion beam, subsequent ion focusing, or charge exchange in a different material (e.g., Cs for polarized-ion source work) ion transport is a problem. In brief, space-charge forces for intense beams are so severe that essentially complete space-charge neutralization is required for useful beam transport (e.g., $\geq$99% neutralization was attained for 1-keV H^+ beams[30]). This is ordinarily accomplished by allowing sufficient background gas for beam ionization to produce a secondary plasma and hence electrons to fill the beam potential well up to within a few kT_e (ambipolar potential) of the walls. Problems arise if the beam is too low-energy to produce sufficient ionization,[42] if instabilities are present to heat the electrons, or if beam modulation in the 100 kHz to few MHz range is present.[10,43] Beam modulation prevents complete neutralization because of either insufficient time for electron buildup or loss of highly mobile electrons to the walls during decreases in beam density.

The ultimate beam transport qualities are determined by the plasma source and extraction system. Values of normalized emittance near 0.1 mrad · cm and high brightness near 10^{10} mA/cm^2 · rad^2 are now fairly common. Because careful qualification is necessary before ion sources are compared, sources of likely interest should be investigated by referring to the specified detailed published work.

Specific Ion Sources as Examples

The Duopigatron-Type Ion Source

Duopigatron ion sources are now among those most widely used for intense beam applications to either accelerators or CTR. Table II lists some of the parameters attained with four selected examples of this type.

ORNL Duopigatron.[5,18,44] This source has been developed by Morgan at Holifield National Laboratory (HNL)* with many applications to CTR and accelerator work. The special features of this source include relatively good power efficiency, high molecular ion fractions, and relatively versatile, high-current, long pulses up to 300 ms at 40 kV. The source is also available in a 10-cm diameter version that incorporates a central Zwischen insert for better plasma uniformity. Axial beam focus to a common point has been achieved by programmed aperture inter-electrode displacement relative to the central axis.

MATS III.[19] The 6.3-cm diameter plasma for this ion source was originally developed for low-energy, steady-state service for beam injection on the Baseball II CTR experiment.[30] Each electrode in the acceleration-deceleration set of electrodes in MATS III is water-cooled, allowing steady-state operation of 1.5-A drain at 20 kV with a mean divergence $\theta = \pm 1.1°$. This source differs from the normal duopigatron in that it was developed with a nonmagnetic (Cu) Zwischen electrode.

Annular Duopigatron.[6] This new type of ion source utilizes a ring-type duopigatron geometry with the plasma coverging along a radial cusp field to the central column for axial extraction. The special feature of this source is the apparent possibility of combining the better power efficiency of a magnetic PIG source with good areal scalability and good radial uniformity.

*Formerly Oak Ridge National Laboratory (ORNL).

Table II. Duopigatron-Type Ion Sources

	Duopigatron (HNL)[5,18,44]	MATS III[19]	Annular D.P.[6]	BPD[15]
Voltage (kV)	15-40	5-20	25	30
Maximum drain (A)	8	1.5	2.8	1.2
Pulse length (ms)	300	Steady state	150	Steady state
Maximum j (mA/cm^2)	400	150	100	260
Arc power (kW)	7	3.5	--	2.6
$\partial n/n$ (%)/diameter (cm)	±30/7	±40/6.3	--/9	10/6
Gas efficiency (%)	~50	~40	--	--
Number of apertures/diameter (mm)	209/3.8	63/4	199/4	7/9
Material	Cu	Cu	Cu	Cu
First gap (mm)	--	4.7	--	--
Cooling	H_2O tubing	H_2O channels	Edge	Edge
H^+/H_2^+ fraction	0.4/0.5	0.7/0.25	--	--

However, extraction in the 10- to 100-G field of the converged plasma column does require special attention in the beam optics to the consequences of Bush's theorem.

BPD Source.[15] This ion source appears as a possibly interesting variant of the standard duopigatron or duoplasmatron. The special feature under test is the use of a set of multiple, duoplasmatron-like arc channels to produce a larger, uniform, primary-plasma surface, instead of the usual duoplasmatron approach to higher current output in which a single primary plasma source produces a secondary larger area plasma in an expansion cup.

The B ~ 0 Ion Sources

The B ~ 0 ion source represents some of the most impressive progress in ion source technology, particularly for intense pulsed beam production for CTR. Table III lists three selected examples of this type of ion source.

The LBL-10 and 50-A Ion Sources.[29] These ion sources, which exploit large-area, multiple-aperture extraction, represent a major gain in progress. The B ~ 0 plasma source developed by Ehlers and Kunkel[4] for this ion source has outstanding uniformity and good freedom from hashy fluctuations. One feature not often noted is the large total effective area of distributed W-cathode filaments. This allows sufficient emission without cathode spotting, and therefore very quiet operation. In addition, the beam extraction optics designed by Cooper et al.[36] and general source development by Berkner et al.[29] make this source one of the most promising for intense, pulsed, neutral beam applications. Prompt charge exchange is considered essential for a useful beam. A longer pulse length (10-s) version of this source is under test for a staged, 5-electrode, low-voltage ion source. A programmed displacement of slots in the 50-A source has been used for one-dimensional focus of the 7 x 35 cm array at 3.5 m.

The B ~ 0 Dimov Ion Source.[21] This ion source was developed for very short pulse length accelerator applications of H^- beams and is described briefly by Sluyters[27] in his review of negative ion sources. It is a relatively compact B ~ 0 ion source employing a hollow LaB_6 cathode and a distributed set of anode plates to carry an intense pulsed-arc discharge. It yields a very dense plasma over a fine 2-cm-diameter array of precision-matched W wire and ribbon extraction electrodes. The yield quoted is up to 3 A H^+ drain at 30 kV for a current density of nearly 1 A/cm^2. Dimov then uses charge exchange in an attached H_2 cell for production of up to 54-mA H^- in a low-emittance beam for accelerator injection.

Surface Plasma Ion Sources

A third very prominent area of recent progress is the field of surface-plasma negative ion sources. The use of Cs on a surface such as W yields a dramatic enhancement of the negative (H^- or heavy) ion flux ejected under surface bombardment. Table IV lists some of the parameters of H^- experiments for accelerator applications.

The Surface-Plasma H^- Sources. Belchenko and Dudnikov of Dimov's group[8] have a series of experiments underway to explore the physical basis of negative ion enhancement by Cs on a W surface. One test[45] shows that, at least in some cases, a ~100-ms reaction time is required for the H_2 and the Cs-coated W surface to react for optimum H^- yield. Up to approximately 10^{17} H^-/cm^2 extraction is permitted before surface treatment is again needed. This surface preparation is presumably a continuous process in the ion magnetron sources under arc-discharge conditions. The details of the surface physics are not clear; perhaps they include

Table III. B ~ 0 Type Ion Sources

	LBL-10-A[29]	LBL-50-A[29]	Dimov[21]
Voltage (kV)	10-20	20	30
Maximum drain (A)	16	80	3
Pulse length (ms)	30	10	0.3
Maximum j (mA/cm^2)	500	500	~1000
Arc power (kW)	~50	~185	--
$\partial n/n$ (%)/size	±6/7 cm x 7 cm	±5/7 cm x 35 cm	--/2 cm diameter
Gas efficiency (%)	30-50	--	--
Aperture geometry	20 - 2 mm x 7 cm slots	2 mm x 7 cm slots	fine slot array
Material	Cu	Cu or Mo	Mo
First gap	2.25 mm	2.25 mm	--
Cooling	none-edge	none-edge	none
H^+/H_2^+ fraction	0.75/0.18	--	--

Table IV. Surface-Plasma Negative Ion Sources[8]

	Planotron	Penning
V (kV)	to 30 keV	to 30 keV
j_{arc} (A/cm^2)	to 100	--
Arc power	450 A/100 V	180 A
j_{H^-} (A/cm^2)	to 3.7	--
Extraction geometry (slot)	1 mm x 3 cm slot	1 mm x 1.5 cm
I (H^-) (mA)	to 900	to 400
Loading	Cs_2CrO_4 + Ti	same
I total extraction	~1.5 A	--
Pulse duration (ms)	1-8	0.2 to 10 ms
Fluctuations	hashy	~no RF
B	1-2 kG	--

either formation of CsH catalyzed by W or a surface layer of H^- (Kishinevskiy[45]). Sluyters and Prelec[46] have also built and tested an ion magnetron ion source similar to that described in Table IV. This area is clearly in its very early stages of understanding and exploitation. Nonetheless, recent work by Middleton[26] and Smith[28] also show enhanced, negative, heavy-ion yield from Cs-coated surfaces.

Other Sources of Interest

The electron cyclotron resonantly heated ECR source of Geller[22] and the electron beam ion source EBIS of Donets[23] both would seem particularly well-suited to multiply charged heavy ions. The electrons in these sources can be heated to or injected at nearly any desired energy, and the problem reduces to sufficient ion residence time and relative species populations for extraction. The principal factor for heavy-ion containment is usually the electrostatic trap formed by the electron beam.

New Types of Ion/Plasma Sources

Several alternate approaches to ion acceleration do not fit easily within the classical plasma source-extraction electrode discussion. Some of the newer approaches under study include:

Pulsed Reflex-Triode Ion Acceleration

Work by Humphries et al.[47] has shown that a very high-voltage PIG-type discharge can be used to ionize H^+ from a hydrocarbon-loaded grid and to permit short-pulse extraction of very intense ion beams. The extracted current is space-charge limited, but is very high because very short extraction gaps d << d(breakdown) are used. The over-voltaged gap breakdown time of about an ion transit time then limits the pulse length. Recent results include over 6 kA of ions in a 50-ns pulse at 300 kV, at ion current densities $j \gtrsim 20$ A/cm^2.

Hall Acceleration

Work by Cole et al.[48] with a multistage Hall accelerator has demonstrated a yield of up to 10-A H^+ at 20 keV in a 10° divergence beam. The energy efficiency is relatively good for this device, but the relatively large $\bar{E} \times \bar{B}$ angular spread of the ion orbits appears as a relatively difficult problem that limits applications.

Coaxial Plasma Gun

Work by Dah Yu Cheng[49] has demonstrated that the high-speed plasma of a deflagration wave from a coaxial gun can be focused. Such a plasma gun could be useful for ~1 to 10-keV ion bombardment applications that require total energies of ~1 kJ/cm^2 in a few-μs pulse.

Collective-Ion Accelerator

Olson et al.[50] propose a form of collective acceleration of ion bunches with the potential well created by an intense pulse of relativistic electrons. This approach could be of particular interest to heavy-ion applications.

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