Review of Latest Developments of Ion Sources

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Abstract

This review will summarize the major technical advances in the field of ion sources during the last years; this topic is frequently reviewed and it is the focus of international conferences (e.g. ICIS 91 in Bensheim, Germany, Sept. 1991) or specialized workshops. Developments of ion sources are stimulated by the numerous applications which can largely be grouped into major areas like particle accelerator injection, ion implantation, lithography, surface processing, isotope separation, neutral beams for fusion plasma heating and thrusters for electric space propulsion. In this review paper emphasis is put on recent developments of ion sources for particle accelerator injection. The latest trends in development are also given.

1. INTRODUCTION

The topic of ion sources is so vast that the latest developments thereupon cannot be reviewed in detail in the brief space available here, therefore the views exposed will necessarily be selective. First of all the apparent diversity of ion sources must be reduced by finding relations between them. Table 1 is an attempt to classify ion sources which are well known by their acronym. The meaning of these acronyms will be given further on in the text. They can be divided into three categories according to the charge state of the extracted ions, i.e. high (HCS), low (LCS) and negative (NEG) charge states. They can also be grouped according to the ionization process: the energy carrier being electrons, photons, high electric fields, high-energy ions sputtering a low-work-function metal surface for producing negative ions or a high-work-function metal surface ionizing atoms (e.g. Li on W at 1200°C).

Arc discharges, where electrons are generated from thermionic filaments, are progressively replaced by microwave discharges where electrons are continuously generated and heated. Furthermore, a microwave plasma cathode has been developed and adapted to a well-known Kaufman source [1].

Higher charge states with moderate intensities can now be produced with EBIS, LPIS or ECR sources. Even very high charge states ($^{238}U^{67+}$), which could until now be generated only by stripping of high-energy ion beams, have been created at very low intensity in a new source called EBIT.

By increasing the magnetic field near the wall of the source chamber, the plasma density can be one or two orders of magnitude higher. This is achieved by covering the walls with permanent magnets, creating a "minimum B" magnetic configuration which confines the plasma. For ECR sources an hexapole is used, for others called "multicusp" ion sources, the walls are covered with permanent magnet bars.

High-current beams of metal ions at low-charge states can

Table 1. Ion source classification by ionization process

Production mechanism	Ionization process	Ion source type	Charge state HCS	LCS	NEG
volume production	microwave or RF discharge	ECR (hexapole)	+		
		ECR(multicusp)		+	-
		off ECR		+	-
	laser	Photo-ionization		+	
	e⁻ beam	EBIS	+		
		EBIT	+		
		e⁻ beam-plasma discharge.		+	
	arc discharge with thermionic filament or cathode	Multicusp		+	-
		PIG	+	+	-
		Kaufman type		+	
		Freeman-Bernas		+	
		Calutron		+	
		Duoplasmatron		+	-
		Magnetron		+	-
surface production	e⁻ capture	surface ionizer		+	-
	field evapor.	LMIS*		+	
	field ioniza.	GFIS		+	
	laser	LPIS*	+		-
	sputter	Multicusp		+	-
	cath. spots	MEVVA*		+	

*Operating without gas carrier.

now be generated with new sources (LMIS, LPIS and MEVVA) working without gas carrier.

Negative ion beams have been improved from several mA to more than 1 A in just twenty years and they are becoming more and more important for applications in accelerators, tokamak reactors and ion implanters.

A recent book entitled "The Physics and Technology of Ion Sources" gives a review of existing ion sources [2].

2. HIGH-CHARGE-STATE ION SOURCES

2.1 Electron-Beam Ion Trap (EBIT)

This source [3], which is a variant of the EBIS has been recently developed for studying interactions of fast electrons with highly charged ions. The EBIT (Fig.1) consists of an electron beam compressed to current densities of up to 6000 A/cm². The electron beam radius is maintained at around 30 μm by the field (B = 3 T) of two superconducting Helmholtz coils. The ion trap is a drift tube which has a length of 20 mm. The electron-beam energy is operated at up to 30 keV and will be upgraded up to 150 keV. Ions are introduced into the trap either by injection from an auxiliary ion source or through ionization of the background gas. For metallic ions the auxiliary source is a MEVVA, which injects ions axially into the trap. Table 2 shows the preliminary performance of this new source.
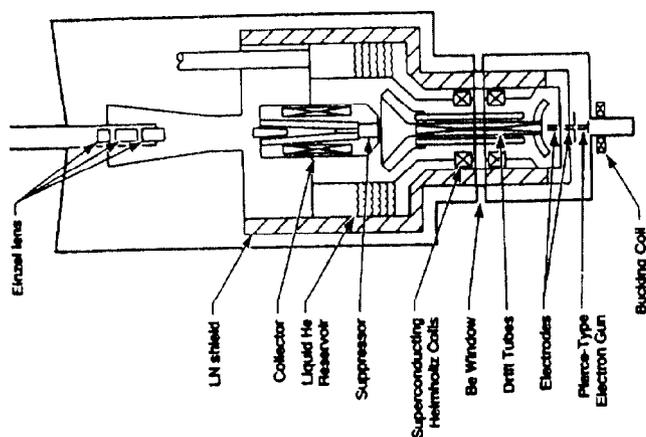
Figure 1. Schematic diagram of the EBIT.

Table 2

ion	number of particles per pulse	electron beam energy (keV)	trapping time (s)
$^{232}Th^{80+}$	$2 \cdot 10^3$	24	3
$^{238}U^{67+}$	$1 \cdot 10^4$	9	4

2.2 Electron-Beam Ion Sources (EBIS)

The progress in increasing the intensity of very high-charge states is slow because of the relatively complicated technology of EBIS construction. Nevertheless, an important breakthrough has been achieved by low-charge-state ion injection and by "ion-by-ion" cooling. With an e⁻ beam energy of 50 keV, Xe^{53+} and Xe^{54+} have been detected in Dubna [4]. Table 3 shows results obtained with Dioné at LNS [5].

Table 3

ion	pulse duration (FWHM) (μs)	peak beam current (μA)	emittance(4RMS) (π.mm.mrad)
$^{127}I^{41+}$	15	0.3*	0.33
$^{84}Kr^{30+}$	25	6.3	0.33
$^{40}Ar^{16+}$	25	6.6	0.33
$^{6}Li^{3+}$	15	20	0.33

* 3.10^7 charges per pulse - repetition rate : 0.5 Hz

Dioné is a cryogenic EBIS into which primary low-charge-state ions, produced by a duoplasmatron or a surface-ionization source, are injected. The $^6Li^{3+}$ mentioned in table 3 is a polarized ion beam. While in the trap, the ions gain energy from the electron beam though electron-ion Coulomb collisions and they can escape from the trap. By injecting 2.10^7 He atoms/cm³ into the ionization zone, a cooling effect on the high-charge-state ions takes place. Thereby the confinement time and the electron beam intensity are increased and the yield of $^{84}Kr^{30+}$ is doubled.

2.3 Electron-Cyclotron-Resonance Ion Sources (ECR)

Presently ECR ion sources are used at some 25 laboratories all over the world. Interesting remarks at the last Workshop on ECR ion sources (Knoxville, Tennessee, Nov., 1990) have been made by R. Geller [6] and A.G. Drentje [7].

In 1979 an important breakthrough was achieved by the availability of hard permanent magnetic materials like SmCo₅, used to build hexapole magnets without electric power. These magnets are able to produce the necessary mag-

netic field (B_{ECR}= 0.36 T) on the closed heating surface in the plasma at 10 GHz. More recently SmCo₅ is being replaced by Nd-Fe-B, which gives a higher magnetic field and the necessary B value (B_{ECR}= 0.51 T) to use the 14 GHz generators which are presently applied in satellite communication and therefore produced at a reasonable price.

Since higher charge states are obtained by increasing the microwave frequency and the magnetic field, a superconducting ECR ion source, which will cover the range from 6.4 to 28 GHz, is being constructed at MSU [8].

The size of the plasma chamber of the new sources has been considerably reduced by increasing the microwave frequency and the magnetic field.

The ion current is increased by a factor of 2.5 using an electron gun in order to inject electrons axially into the plasma (Fig. 2) [9]. By coating the plasma chamber wall with SiO_2 [9] the source performance is also improved, but this effect decreases after 10 hours.
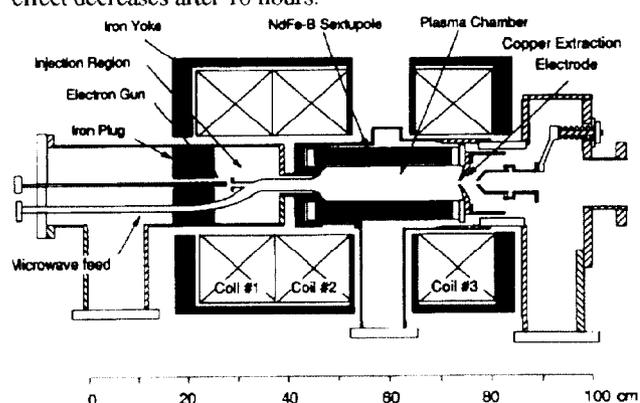
Figure 2. Schematic drawing of the LBL advanced ECR ion source (14 GHz) using an electron gun.

Usually high-charge-state beam currents are substantially increased when a lighter gas is mixed into the plasma. Observing that gas mixing, in general, has the effect of reducing the energy spread of extracted beams, T.A. Antaya tried a model [10] for this effect based on "ion cooling".

Metallic ions are produced by heating a solid sample directly in the plasma or by evaporating a piece of metal in an oven. A very expensive isotope such as ^{48}Ca has been accelerated [11] at a very low consumption rate (2 mg/h).
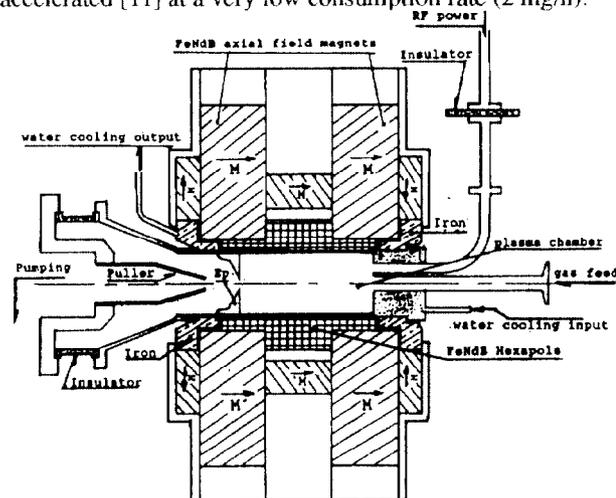
Figure 3. Schematic view of NEOMAFIOS 10 GHz

In pulsed operation mode, high-currents of high-charge-state ions are obtained during the 1 ms afterglow [12-13].

A new source (NEOMAFIOS 10 GHz) [14-39] (Fig 3) has been constructed in Grenoble entirely with Nd-Fe-B permanent magnets which have a remanent field of 1.2 T. The total electric power consumption is only 6 kW and the performances are similar to those of the classical 10 GHz sources. Oak Ridge has presented a proposal [15] to install such a source in the terminal of the tandem electrostatic accelerator at 24 MV. Some remarkable new achievements which were reported recently are shown on table 4.

Table 4. Yield of high-charge-state ions.

ion	operating mode	beam current (eμA)	laboratories and references
$^{40}Ar^{14+}$	DC	17	LBL [9]
$^{40}Ar^{18+}$	DC	0.02	Grenoble [16]
$^{84}Kr^{25+}$	DC	0.8	Jülich [17]
$^{129}Xe^{31+}$	DC	1	LBL [9]
$^{197}Au^{25+}$	DC	5	Grenoble [18]
$^{207}Pb^{28+}$	DC-pulsed	22 - 100*	GANIL [13]
$^{207}Pb^{31+}$	DC	8	GANIL [19]
$^{238}U^{31+}$	DC	1	Grenoble [18]

*Afterglow (0.5 ms) in pulsed mode (50 ms -7 Hz)

Table 5 shows emittance measurements performed with light ions from gases like H_2 and He at 90% of the total beam current. The extraction voltage is 7 kV for H_2^+ (β=2.73 10^{-3}), 15 kV for He^+ (β=2.82 10^{-3}) and 40 kV for H^+.

Table 5.

ion and beam current (μA)	hole diameter (mm)	norm. emittance (4 RMS) [20] (π mm mrad)	laboratories and references
H_2^+ (85)	7	0.068	Jülich [21]
He^+ (200)	6.5	0.19	GANIL [19]
H^+ (25000)	4	0.28	Chalk River [22]

3. NEW METAL ION SOURCES

3.1 Field emission Liquid Metal Ion Sources (LMIS)

The LMIS [23] is composed of a thin needle substratum which is coated with a liquid metal (Fig. 4).

(a)   (b)
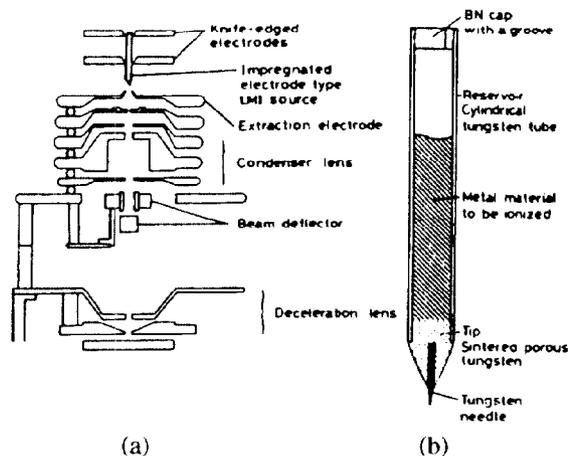
Figure 4. (a) Diagram of the ion beam focusing system
(b) Impregnated-electrode-type LMIS

A potential of several kV is applied between the needle and an extraction electrode in a vacuum better than 10^{-7} mbar. The electric forces cause the liquid surface to form a conical shape at the needle apex from which ions are emitted. The needle-point emission site has a tip radius estimated in the range of 10 to 100 nm and a surface electric field at the tip radius in the range of 10^7 V/m.

A metal ion beam current from 10 to 100 μA with a charge state of one or two can be extracted. The energy spread is less than 10 eV and the ion temperature as low as 1 eV.

The LMIS emittance is extraordinary low due to the small surface of the emission point and the low ion temperature. The focused beam size, reaching 0.5 μm, is only limited by chromatic aberrations. Lifetimes of several 100 hours with stable beams are obtained.

Recently an impregnated-electrode-type LMIS has been developed (Fig. 4 b). The porous tip is made of refractory metal, typically tungsten, by sintering a mixture of powders with granule diameters of 10 and 100 μm. The ion source has a cylindrical reservoir made of tungsten which is heated for melting the metal that is to be ionized. The flow rate of liquid metals, whose vapor pressure at their melting point is as high as 10^{-3} mTorr (Cu, Ag), can be controlled by the porous region. The number of emission points has been increased up to eight and it has been shown that the ion current is proportional to this number.

The LMIS has found applications in a number of new technologies, e.g. beam lithography, submicron focusing, maskless implantation, thin film deposition, surface analysis and electrostatic space propulsion. The gaseous field ion source (GFIS) is a similar source operating with gases.

3.2 Metal Vapor Vacuum Arc ion sources (MEVVA)

The MEVVA ion source (Fig.5) [24] is a new kind of source in which a metal vapor arc without gas carrier is used as the plasma medium from which the ions are extracted.

A trigger electrode initiates the discharge by a 4 μs wide and 12 kV high voltage pulse. Micron-sized spots in which the current density can be over 10^6 A/cm^2 appear on the cathode surface, where material is vaporized and ionized. Individual spots have been observed to move around on the cathode surface, each generating a few amperes of current. A strong pressure gradient causes the plasma generated within the spot to plume away from the surface. This source can be operated with an arc current of 150-350 A with a 0.25 ms pulse width and a repetition rate of 15 pulses per second. The maximum peak ion current produced is 3.5 A for an extraction voltage of 80 kV and an extraction hole diameter of 10 cm.
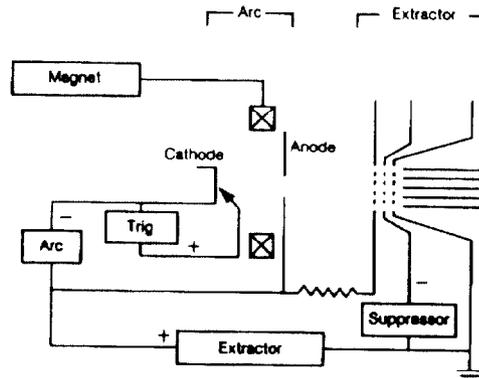
Figure 5. Schematic of the source electrical configuration

Recently some novel features have been incorporated, namely the ability to switch between up to 18 separated cathode materials and the construction of two sources, a broad beam version with à 50 cm diameter extractor and a miniature version of "thumb size".

Beams of solid metallic elements and some metallic alloys have been produced with this source which is finding application for metallurgical ion implantation.

3.3 Laser-Plasma Ion Sources (LPIS)

The future of this source, providing in pulsed mode high peak currents of high-charge-state ions from a small spot, could be very promising. Some laboratories begin to investigate the feasibility of using LPIS for future accelerators (see table 6) and for ion implantation [25] devoted to surface modification. Commercially available machines for ion beam analysis (resolution: 100 nm) are built in the Ukraine.

Table 6

ion	peak beam current (μA) and pulse length (μs)		laser power density (W/cm^2) rep. rate (Hz)		laboratories, applications and references
^{28}Si^{4+}	0.006 (3 GeV/u)		1.10^{10}	0.3	ITEP (Moscow) synchrotron [26]
^{52}Cr^{13+}	100	1	1.10^9	1	JINR(Dubna)
^{7}Li^{2+}	0.1(average)	1	2.10^9	25	U200 cyclotron [27]
^{207}Pb^{26+}	5	6	3.10^{11}	0.25	CERN test bench [28]
^{56}Fe^{4+}	1 (400 kV)	5	6.10^8		Garching Van de Graaff [29]
^{181}Ta^{21+}	2	5	4.10^{13}		test bench [30]
^{12}C^{3+}	75	6	1.10^{11}	50	UNIV. of Arkansas test bench [31]

When a laser beam is focused upon the surface of a solid target on a spot diameter smaller than 200 μm with a power density greater than 10^8 W/cm^2, matter is vaporized and then highly ionized. A plasma rapidly expands perpendicularly to the target surface and the highest charge states produced are projected into a small angle. The charge state multiplicity and the mean ion kinetic energy (10 keV for a power density of 10^{12} W/cm^2) increase with the laser power density on the target. The emittance of the extracted beam should be small, due to the small diameter of the spot on the target.

The major drawbacks of this source are the low repetition rate (50 Hz) and the large energy spread of the ions which is of the same order of magnitude as the mean ion kinetic energy. Moreover, craters having diameters near 300 μm are produced after about 100 shots on a static target and a degradation of the ion output occurs ; therefore the target must be rotated. Users of LPIS utilize two kinds of laser : Nd-YAG and CO$_2$ lasers operating at 1.06 and 10.6 μm wavelength respectively. Recently, the ion currents were enhanced by electron injection in the plasma to compensate for the space charges [30].

4. NEGATIVE ION SOURCES

4.1 Negative Hydrogen and Deuterium Ion Sources

Negative hydrogen ions [32] have been used for several decades in tandem Van de Graaff accelerators where they are accelerated to a high potential, stripped to protons and accelerated to ground, gaining an energy twice the potential.

They also have been used in cyclotrons where extraction is achieved by stripping H$^-$ ions. Duoplasmatron, Magnetron and PIG source studies are being pursued for these types of accelerators. New sources with a magnetic multipole bucket chamber and called "multicusp sources" are intensively studied for fusion programs and modified versions of these sources are used for accelerators (LAMPF, KEK, TRIUMF, BNL, etc.).

Multicusp sources can produce a large volume of uniform and quiescent plasma; they are divided into two types: surface-conversion and volume-production ion sources and are designed for DC operation delivering more than 1 A of H$^-$ or D$^-$. The volume-production of H$^-$ was demonstrated in 1979 by a French group at Ecole Polytechnique near Paris; this group is pursuing this development [40].

It is well known that the injection of cesium enhances by a factor of 4 the production of H$^-$ or D$^-$ in the multicusp sources, but it contaminates the accelerator leading to possible breakdowns. The surface-conversion source produces negative ions with transverse temperatures in the range of 5 to 10 eV compared with 0.5 to 1 eV for the volume-production one, thus giving smaller emittances.

In surface-conversion sources the negative ions are produced by single-electron capture performed by absorbed neutral atoms or double-electron capture of reflected positive ions on a low-work-function surface, such as a monolayer of cesium or a bulk of barium metal. In these sources cesium coated molybdenum converters are replaced by solid barium
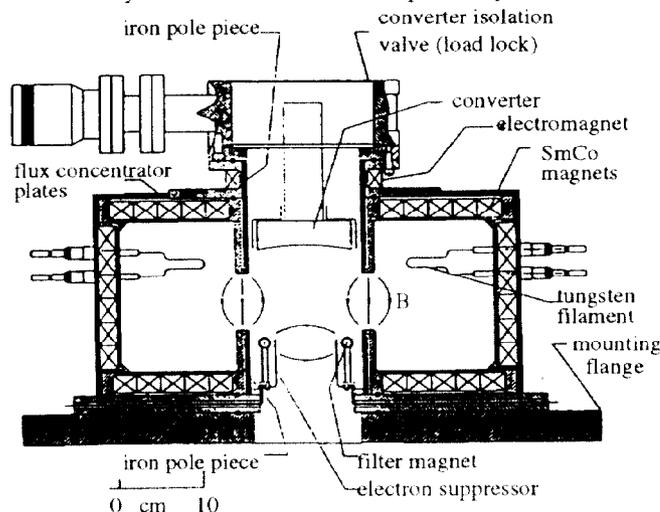
Figure 6. Schematic diagram of the LBL barium converter surface-production source (XBL919-2009)

converters, barium being a much less volatile material. Such sources (Fig.6) are developed at LBL [33] to produce high-intensity in steady-state H$^-$ or D$^-$ beams to be used for the next generation of tokamak reactors. The LBL prototype produces 145 mA of D$^-$ with a 10 cm diameter converter.

In volume-production sources the negative ions are produced directly within the plasma discharge via dissociative attachment of vibrationally excited molecules. When they are operated without cesium vapor, the high pressure (10 mTorr) in these sources results in a significant beam loss due to stripping of the negative ions and in a large amount of leakage e$^-$ mixed into the negative ion beam. The lifetime of the source being limited by the erosion of the filament, the tendency is to replace the filament-driven arc plasma by a RF-driven plasma in the volume-production source.

A new RF-driven H⁻ source recently has been developed at Culham [34] and at LBL [35](Fig.7) the latter for future use in the injector of the Superconducting Super Collider (SSC).

For heating and driving fusion plasma, neutral beams of deuterium will be injected through high magnetic fields into reactors. The next generation of tokamaks like ITER (International Thermonuclear Experimental Reactor) and NET (New European Torus) needs a total beam power of 75 MW accelerated at 1.3 MeV. ITER envisages the use of nine neutral beam modules divided over three ports to deliver this power. For this program multiamp D⁻ ion sources are needed. These negative ions are accelerated and then converted to atoms with efficiency better than for positive ion conversion.
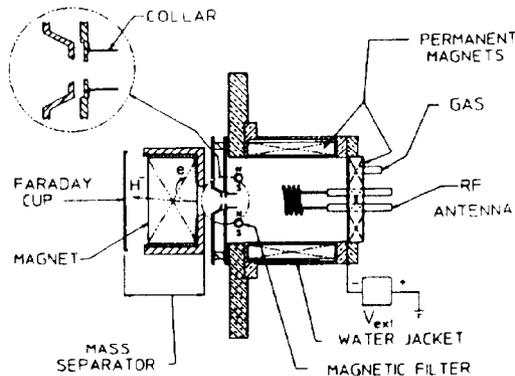
Figure 7. Diagram of the LBL multicusp volume-production source operating with an rf induction coil (1.8 MHz) and producing 200 mA/cm² of H⁻.

4.2 Negative Heavy Ion Sources

Negative heavy ion sources [36] are now being considered for implanter applications. These types of sources reduce the problems of surface charging and impurity ions.

Recently requests for intense metal ion beams [37] have increased abruptly, in particular for applications in surface modification by metal ion beams. Negative ion sources, unlike the positive ones, deliver monoenergetic beams with only one charge state and might be the most suitable source for this application. A sputter-surface-conversion source (Fig.8) with ECR discharge in Xe gas, using cesium, has been developed at KEK [38]. In preliminary experiments a beam current of 7 mA for Cu⁻ was obtained in pulsed operation mode.
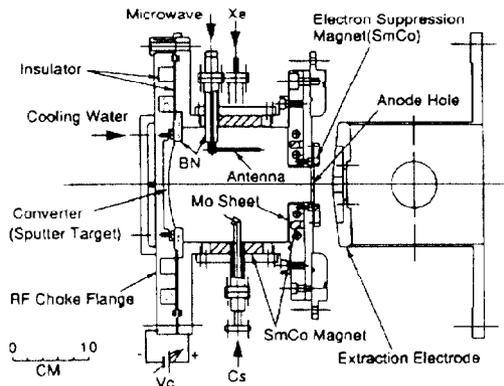
Figure 8. Schematic diagram of the KEK sputter-surface-conversion source with ECR discharge (2.45 GHz).

5. CONCLUSION

The field of ion source technology is growing rapidly. Remarkable progress recently has been made in producing high-charge-state ions (U⁶⁷⁺ with an EBIT at Livermore, Xe⁵⁴⁺ with an EBIS at Dubna, Xe³¹⁺ with an ECRIS at LBL and Pb²⁶⁺ with a LPIS at CERN). Intense metal beams can now be produced with new sources operating without gas (LMIS, MEVVA). Requests for negative ions is increasing rapidly for fusion reactor applications and metallic ion implantation. In the past few years the progress in understanding H⁻/D⁻ beam generation has been impressive and the value of the extracted current has been improved from several mA to more than 1 A. Finally it has been shown that new ion sources are under development and the future is promising for new achievements.

6. ACKNOWLEDGEMENTS

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