ION SOURCES

Joint ICTP-IAEA Workshop on Accelerator Technologies, Basic Instruments and Analytical Techniques

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Ion source

An ion source is a plasma generator from which beams of ions can be extracted. Ion sources have uses in a variety of research fields and applications such as mass separation, ion implantation, fusion, atomic physics and in accelerators for nuclear and particle physics.

Although the acceleration of particle beams is understood by accelerator physicists, the source of the primary particles is often cloaked in mystery.

Different types of ion sources

- Surface ionization
- Field ionization
- Sputter
- Laser
- Electron beam ionization
- Arc discharge
- Multipole confinement
- PIG ion source
- Charge exchange
- Plasma beam
- Duoplasmatron
- Hollow cathode
- Pigatrons
- Multifilament
- Cyclotron resonance
- Surface plasma
- Magnetrons
- RF plasma

Production of positive ions

- In any gaseous discharge, both negatively and positively charged particles exist in approximately equal proportions along with un-ionized neutrals, i.e. they form a plasma.
- Electron bombardment ionization of the neutrals in the plasma is the most general method of increasing the plasma density. Energetic electrons passing close to, or colliding with, an electron orbiting an atom can give energy to that electron. It then moves to a higher metastable orbit.
- The ionization potential is only a threshold; ionization efficiency increases with incident electron energy up to about three times the ionization potential and falls off at higher energies.

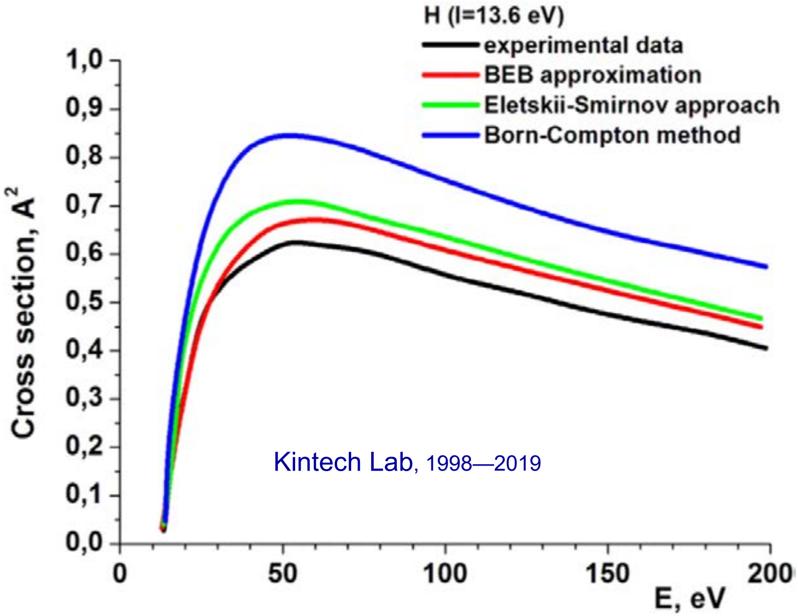
Ionization of atoms

- The ionization energy of atoms is the minimum energy required for a successful ionization.

- Electrons are the most effective particles for the ionization of atoms due to the laws of conservation of energy and momentum resulting in that most ion sources are electron bombardment ion sources.

- For gases the ionization energies varies between 12.1 eV (O_2) and 24.6 eV (He).The ionization energies of H_2 molecule is 15.4 eV for H atoms 13.6 eV.

- The optimum ionization cross section is about 3 times the ionization energy.



- How can we produce electrons,

Thermionic generation of free electrons

For metal atoms the conducting electrons are bounded to the metal with a potential called the work function. This is the energy require to remove an electron from the metal and it lies between 4.5 to 6 eV.

Some of the electrons will gain enough energy to overcome the work function and escape from the surface of the metal if the metal is heated.

Applying a negative voltage to a filament the electrons that can be removed from the filament is given by

$$j = AT^2 e^{\varphi/(kT)}$$

j = electron current density
k = Boltzmann constant
φ = work function
T = temperature in kelvin of the metal
A = Richardson's constant of the emitter

Electron ion source used for ionization

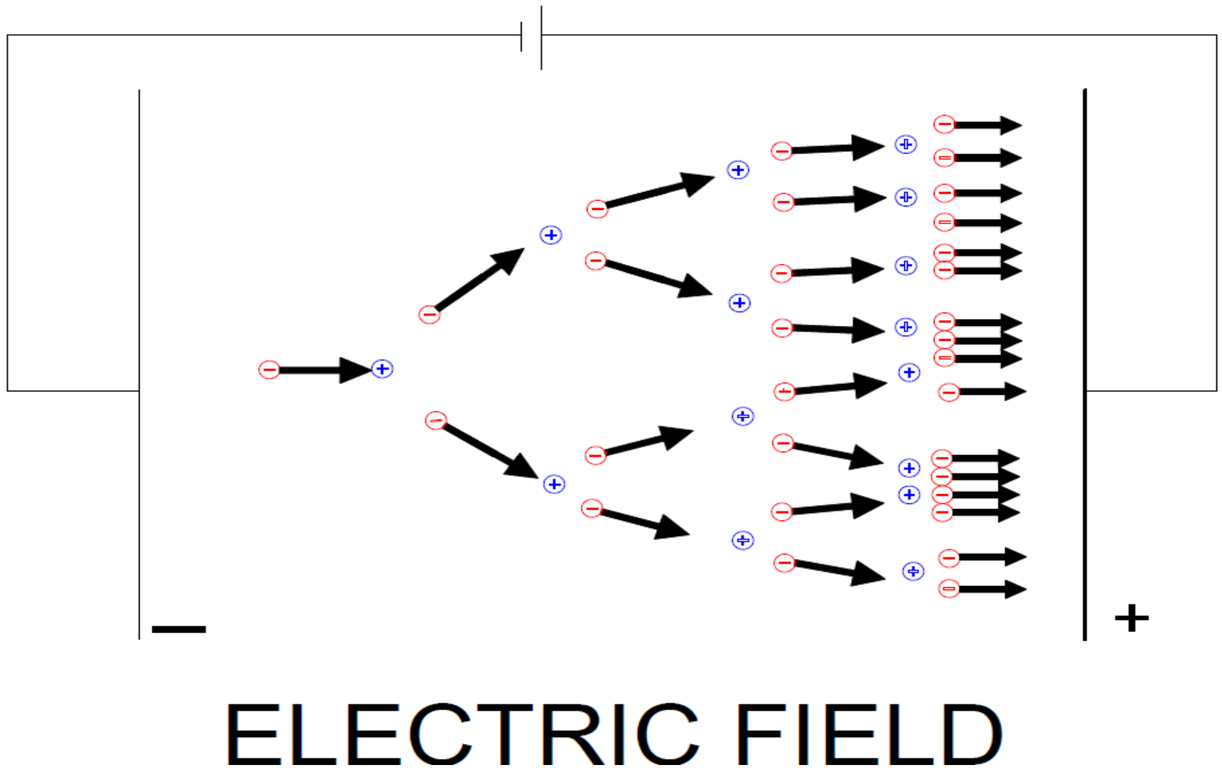
- Electron bombardment ion sources used thermionic emission from a hot filament to generate electrons.
- By applying about 100 volts negative voltage to the filament the electrons will gain suffusion energy to ionize all gas atoms and molecules.
- The filament lifetime is limited by sputtering of the filament by the positive ions.

- At about 1 milli bar pressure it take about 300 electrons to produce 1 ion. Not very effective for producing high beam currents.

- How can we increase he number of electrons

Townsend discharge

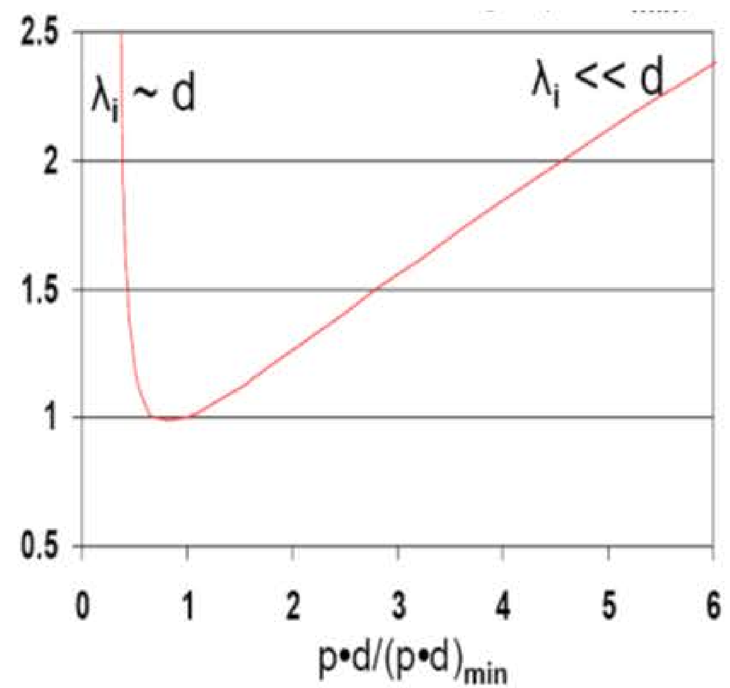
- With the Townsend discharge the ionization rate can be exponentially increased.
- The Townsend discards takes place in an electric field when the energy gain of the electrons between collisions is more than the ionization energy of the particle to be ionized. The gas pressure and the electric field must allow the electrons to pick up sufficient energy between subsequent collisions. If the ionizing and the ejected electron will gain suffusion energy before the next collision to ionize the next atoms or molecules an avalanche will start.
- The discharge will grow exponentially with the distance, d between the anode and cathode if the voltage is increased proportional with the distance d.



Breakdown Voltage (Paschen's Law)

- The voltage at which a low pressure gas breaks down depends on the ratio of the distance between the electrodes, d, and the mean free path $\lambda_{ionization}$ or p.d the product of the gap d and the pressure p.
- The secondary electron emission coefficient of the cathode material determine the minimum breakdown voltage.
- From the graph follows no breakdown at very low and very high pressure.
- To start an ion source one normally apply the arc voltage and slowly increase the gas pressure till the plasma ignite.

Breakdown voltage V/V_{min}



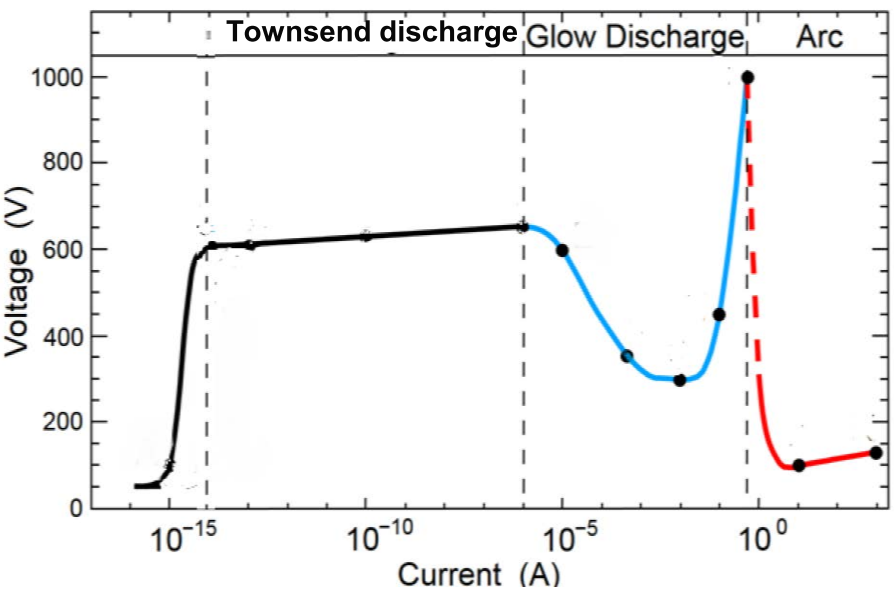
Electrical discharge in low pressure gases

Electric discharge in gas has three regions:

Townsend discharge, below the breakdown voltage. At low voltages, the only current is due to the generation of charge carriers in the gas by cosmic rays or other sources of ionizing radiation. As the applied voltage is increased, the free electrons carrying the current gain enough energy to cause further ionization, causing an electron avalanche. In this regime, the current increases from femtoamperes to microamperes, i.e. by nine orders of magnitude, for very little further increase in voltage. The voltage-current characteristics begins tapering off near the breakdown voltage and the glow becomes visible.

Glow discharge, which occurs once the breakdown voltage is reached. The voltage across the electrodes suddenly drops and the current increases to mA range. At lower currents, the voltage across the tube is almost current-independent. At higher currents the normal glow turns into abnormal glow, the voltage across the tube gradually increases, and the glow discharge covers more and more of the surface of the electrodes. Most ion sources operate in the glow discharge region.

Arc discharge, which occurs in the ampere range of the current; the voltage across the tube drops with increasing current.



The processes in a hydrogen plasma

H_2 + 'ionization'	$\Rightarrow$	$H_2^+ + e$
$H_2 + e$	$\Rightarrow$	$H_2^+ + 2e$
$H_2^+ + e$	$\Rightarrow$	$H^+ + H + e$
$H + e$	$\Rightarrow$	$H^+ + 2e$
$H_2^+ + H_2$	$\Rightarrow$	$H_3^+ + H$
$H_3^+ + e$	$\Rightarrow$	$H^+ + H_2 + e$

Typical ionization potential ranges

Ion	Ionization Potential (eV)
Oxygen 5+ to 6+	138.1
Oxygen 0+ to 6+	433.1
Oxygen 7+ to 8+	871
Lead 26+ to 27+	874
Lead 0+ to 27+	9200
Lead 81+ to 82+	91400

The maximum charge state that can be attained is limited by the maximum incident electron energy.

Multi-step ionization is thus the only really feasible route to high-charge-state ions but this process takes time.

Charge state distribution

- The charge state distribution is mainly determined by the energy of the electrons and the product of electron current density and containment time.

- The diffusion time out of the ionization volume without any confinement is in the range of μs. By special magnetic and electric fields containment times up to s can be achieved if charge exchange is negligible.

- The dominant charge exchange process is with neutral atoms. The charge exchange between ions is much smaller because of Coulomb repulsion.

The life-time is in the range of tens of ms for a residual gas pressure in the range of 10^{-4} to 10^{-5} pascal.

- High j_e and n_o lead to high current, but not to high charge states because of short τ_c.
- High electron energy, low pressure and long containment is needed for high charge states.

Charge state distribution a multi step process

The time necessary for an atom to reach a certain charge state depends on the cross section and the electron current density

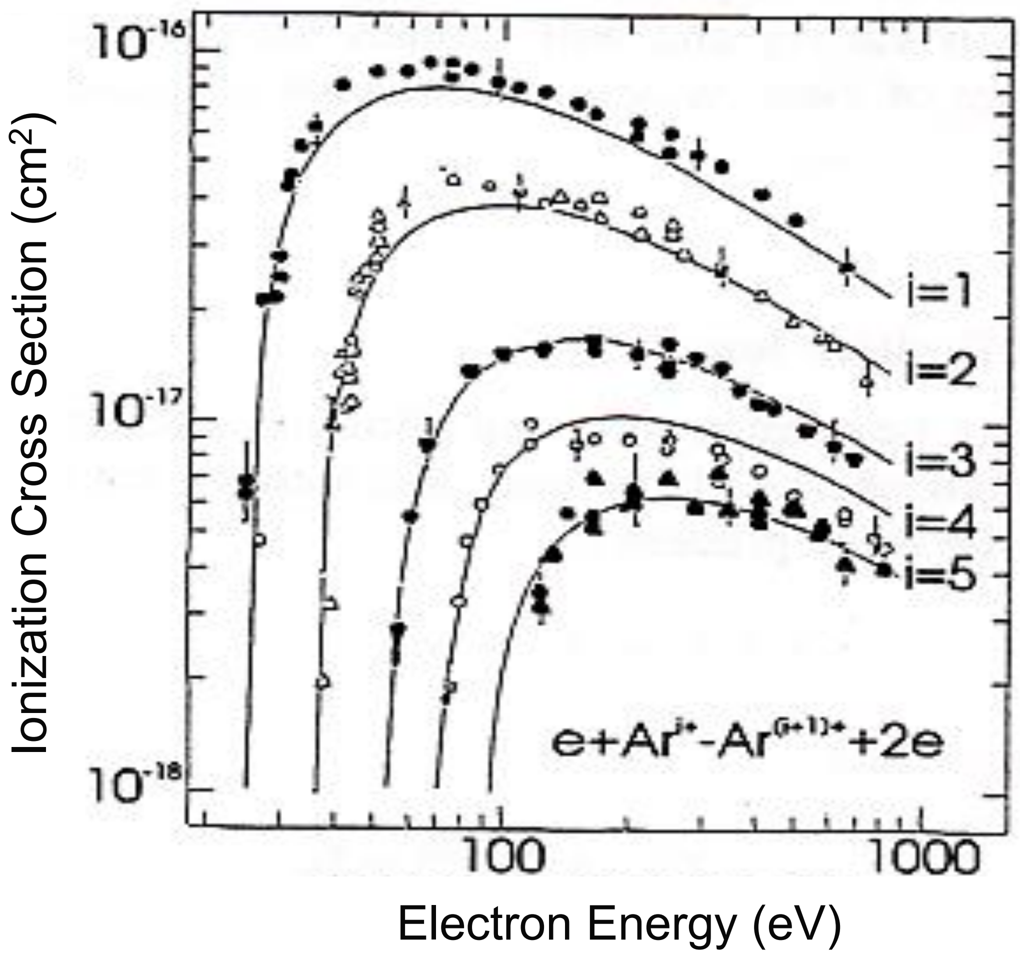
$$dn_0/dt = n_0 \sigma_{0,1} j_e$$

and

$$dn_i/dt = n_{i-1}\sigma_{i-1,i} j_e - n_i \sigma_{i,i+1} j_e - n_i/\tau_c(i)$$

n_0	is the neutral particle density
n_i	is the ion density in charge state i
$\sigma_{i-1,i}$	is the cross section for single step ionization into charge state i
j_e	is the electron flux density
$\tau_c(i)$	is the life time of ion in charge state i (containment time) without ionization

Ionization cross-section as a function of the bombardment energy of electron for different charge states



Characteristics of an ion source are determined by the plasma and the extractor

Ion beam current

Determined by plasma density, plasma electron temperature, extractor voltage, extractor geometry.

Beam emittance

Determined by plasma density distribution, plasma ion temperature, extractor geometry, extraction voltage.

Beam composition

Composition of the plasma, pressure in source.

Ion sources for positive ions

High Current Ion Sources

Filament ion sources

In its simplest form a high-current ion source consists of a cathode filament surrounded by an anode cylinder or cube and an aperture in the extraction plate opposite the cathode. The end plates E1 and E2 can be at anode, floating or near cathode potential to reflect the electrons to provide a higher ionization efficiency.

- Discharge is ignited at a gas pressure of 10^1 to 10^{-1} pascal. Such a device needs a high discharge current because of the large anode area.
- With the availability of strong permanent magnets multi-cusp devices are more and more used to create the plasma needed in high-current sources for singly-charged ions.
- The discharge vessel is surrounded by magnets with alternating polarity, creating a minimum-B configuration which reduces the effective anode area and yields a quiet, homogeneous plasma of large cross-sectional area.

Important aspects to create high current ion sources

- The density of a plasma is dictated by the balance between production and loss processes, with the added restriction to maintain neutrality, the ion charge and electron charge densities must be equal.

- Energetic electrons, which are more useful for ionization, are more easily lost to the chamber walls than the slower ions unless steps are taken to return the fast electrons to the plasma. It would also be of advantage to allow slow electrons with less than the minimum ionization energy to escape thus reducing the possibility of electron-ion recombination. A strong multipole magnetic field surrounding the plasma volume meets these requirements.

- The increased path length of the energetic electrons increases the probability of ionization, whilst cold electrons spiraling down the field lines have more chance to be lost on the walls. Improvements in ionization efficiency result in a reduction of neutral pressure for the same plasma density which can make for a more open source and ease vacuum pumping requirements.

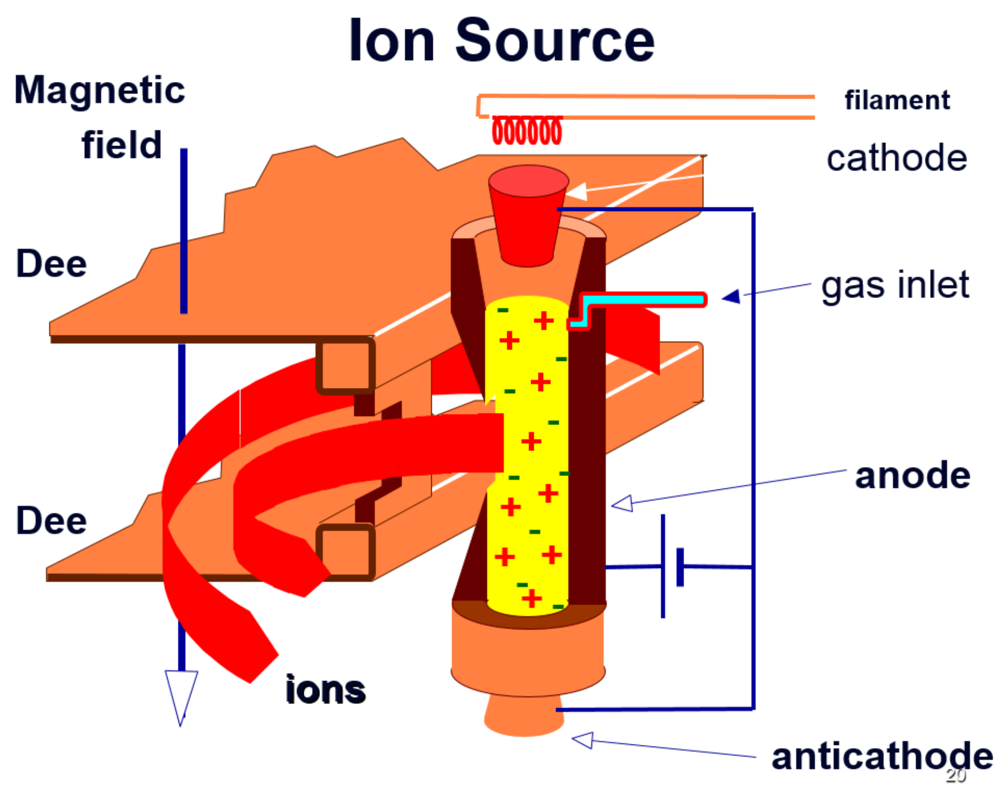
PIG ion source

The PIG ion source consists of the two cathode blocks and a cylindrical anode in a magnetic field parallel to the anode axis.

In the PIG source electrons are emitted from one cathode, follow the B-field lines to the other cathode, and are reflected there.

The electrons oscillate in this way a few times through the discharge thereby increasing the electron current density.

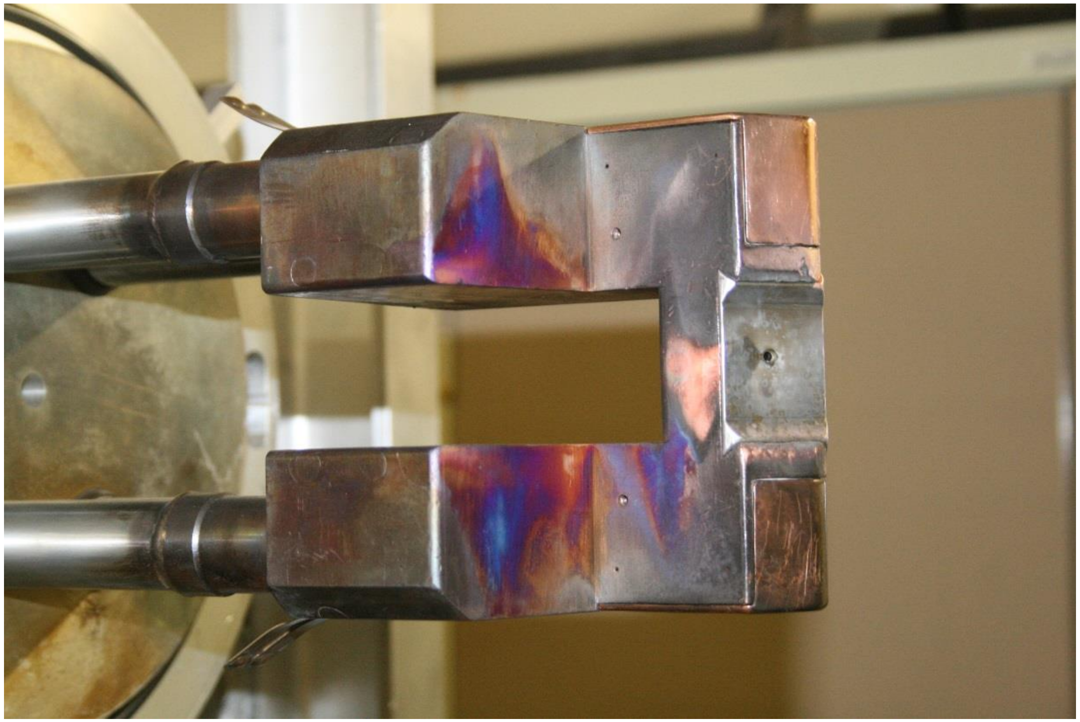
Ions can be extracted either axially, through a hole in one cathode or, as is commonly done, radially through a slit in the anode, using the magnetic field simultaneously for charge analysis.



PIG ion source continued

As previously mentioned to get the maximum value for the total ionization cross section and hence the maximum production rate for the ions, the electron energy must be about three to five times the ionization energy for step-by-step ionization of the charge state considered. Therefore, it is advantageous to control the arc impedance and hence the electron energy. This is achieved by applying additional heat to one cathode by an electron current from a filament and also by varying the gas flow to the source.

iThemba LABS PIG ion source for solid pole injector cyclotron 1



Typical source parameters
Hydrogen gas flow 12 sccm
Arc voltage 110 V
Arc current 2-3 A
Filament current 190 A
Extracted proton current 4 - 5 mA

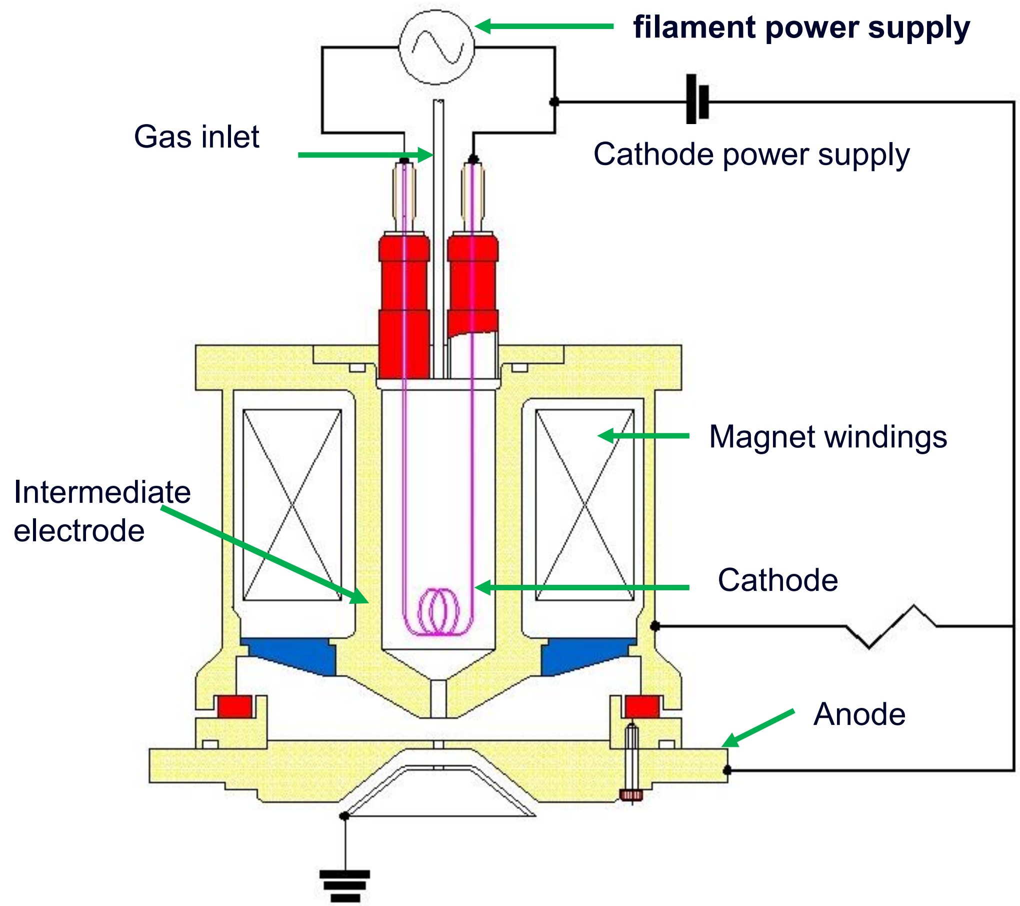
Duoplasmatron ion source

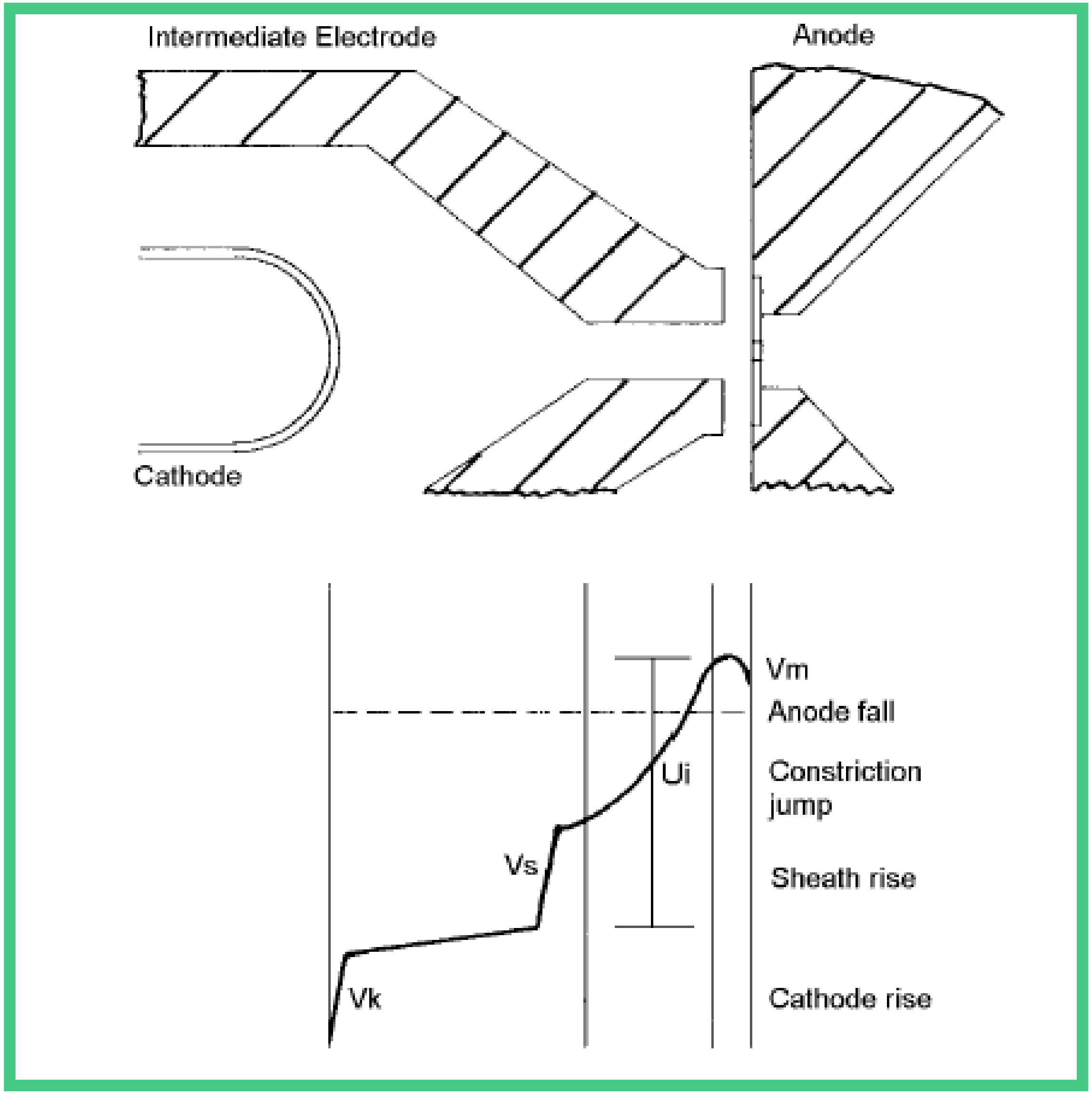
- The discharge plasma is

An ion source which has been in use for many years, both for the production of high-current proton beams and low-charged, positive heavy ions, is the duoplasmatron source.

- Due to the constrictions of the discharge, one or more double layers are generated along the plasma column. Separating regions of different neutral pressure and plasma density.

- Near the anode there exists a relatively dense plasma with a high degree of ionization, whose potential is higher than that of the anode. The ions are extracted through a small outlet aperture in the anode.





The discharge region of duoplasmatron ion source and an idealized potential distribution in the constriction

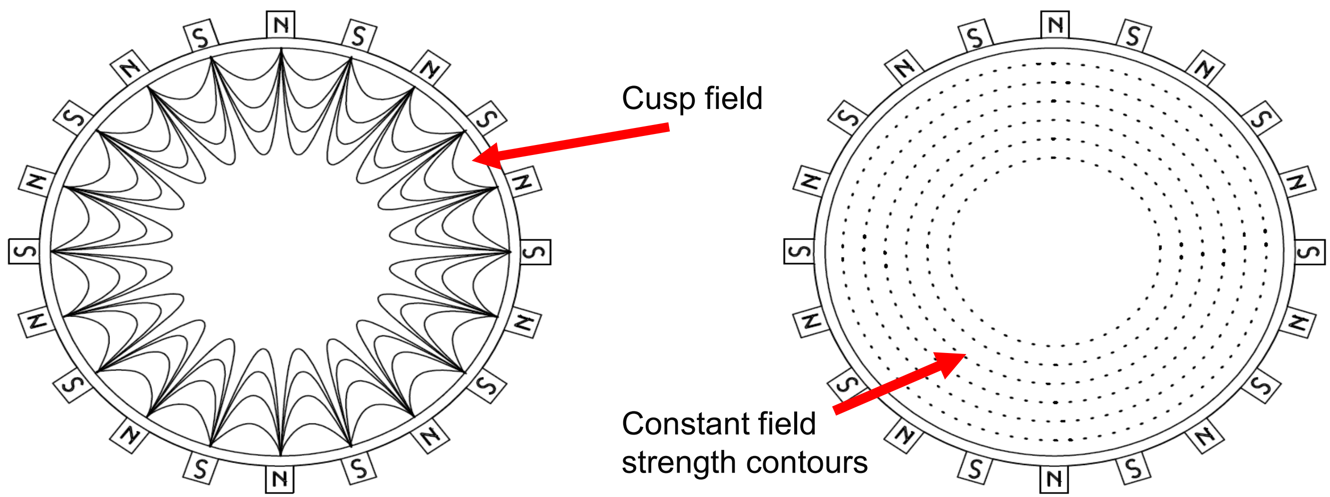
Duoplasmatron ion source used at the old Van de Graaff accelerator

Duoplasmatron Operational Parameter

- Mesh Cathode, Coated with 50% Barium nitrate, 45% Strontium nitrate, 5% Calcium nitrate mixed in alcohol, needs outgassing typically 3-4 hours, app.
- Cathode operation: 20A, 4V
- Anode (Arc) Electrode: 100V, 1A
- Magnets: 20V, 1A
- Source needs cooling (Si based coolant)
- Gas consumption: 1l container, 17bar for 7 weeks, 0.25sccm
- Outlet aperture diameter 0.2mm
- Extraction Voltage: typical 3kV, pulsed operation up to 15kV
- Accelerated current: H^+ : 8μA, He^{2+} : 3μA, pulsed operation up to 100μA, duty cycle app. 1-2%, $H^+/(H^+ + H_2^+ + H_3^+) < 50\%$
- Maintenance: Period max. 6 weeks, cleaning source body and filament, applying new coating

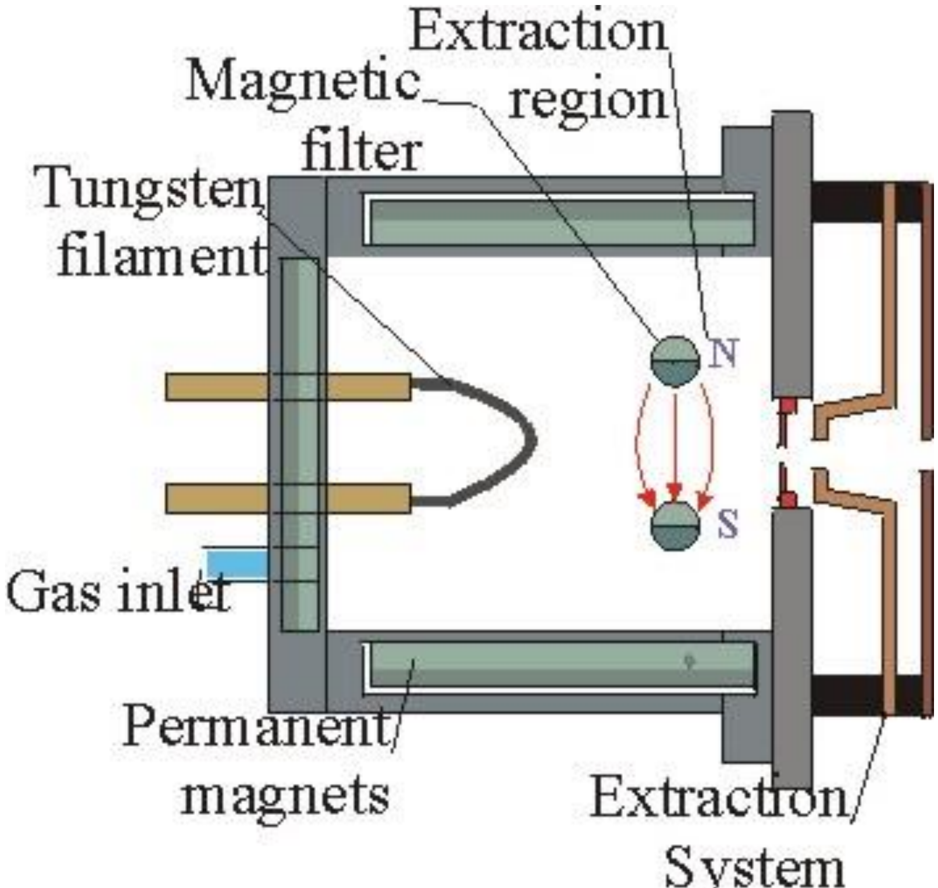
Multicusp ion source, magnetic field

Multicusp ion sources use permanent-magnets to confine the primary ionizing electrons and the plasma. The magnets are arranged in such a way as to generate line-cusp magnetic fields. The magnetic field strength B is a maximum near the magnets and decays with distance into the chamber. Most of the plasma volume can be virtually magnetic-field free, while a strong field can exist near the discharge chamber wall, inhibiting plasma loss and leading to an increase in plasma density and uniformity.



Magnetic multicusp confinement in cylindrical geometry, illustrating the magnetic field lines and the constant B surfaces near the circumferential walls.

Multicusp ion source



A permanent-magnet "filter" shown schematically can be installed in a multicusp ion source. The filter improves the atomic hydrogen or nitrogen ion fraction, the plasma density profile at the extraction plane, and the uniformity of the plasma potential along the axis. Atomic ion species >90% can be obtained for the diatomic gases such as hydrogen and nitrogen by the use of the magnetic filter.

Multicusp fields have been found to have three important effects on low-pressure plasma discharges

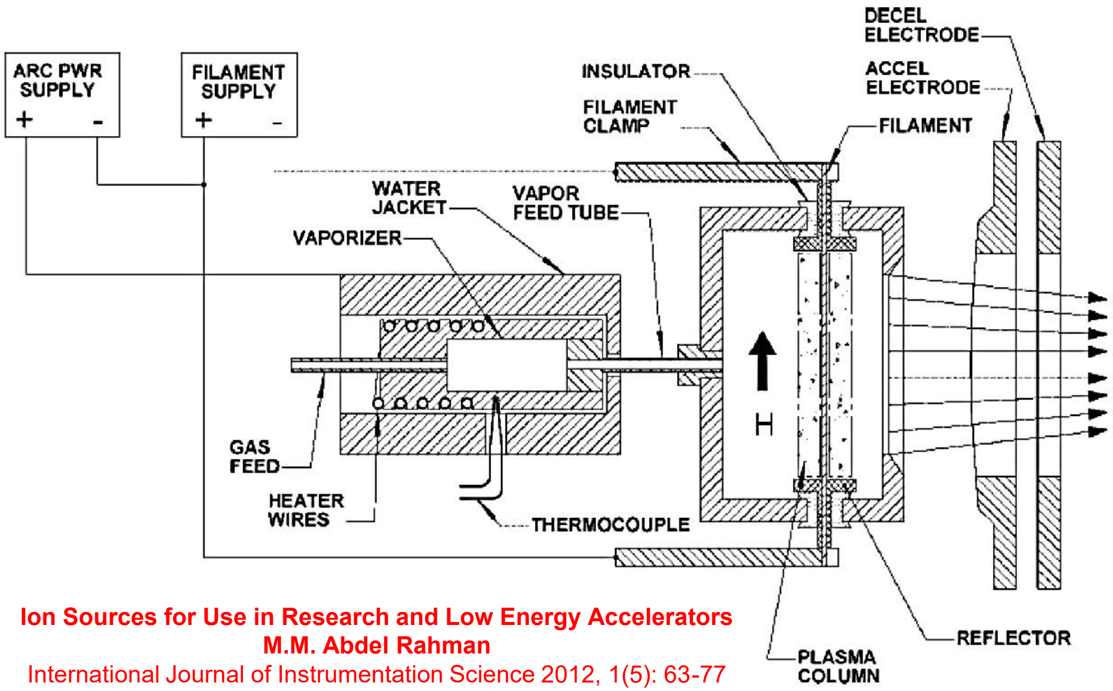
Plasma can be generated in a multicusp ion source by dc discharge or rf induction discharge.

1. High energy electrons can be efficiently confined. These electrons are the ionization source for a discharge.

2. Significant improvements can be obtained in the confinement of the bulk plasma in a discharge.

3. Significant improvements in radial plasma density and potential uniformity can be achieved.

Freeman ion source



Ion Sources for Use in Research and Low Energy Accelerators
M.M. Abdel Rahman
International Journal of Instrumentation Science 2012, 1(5): 63-77

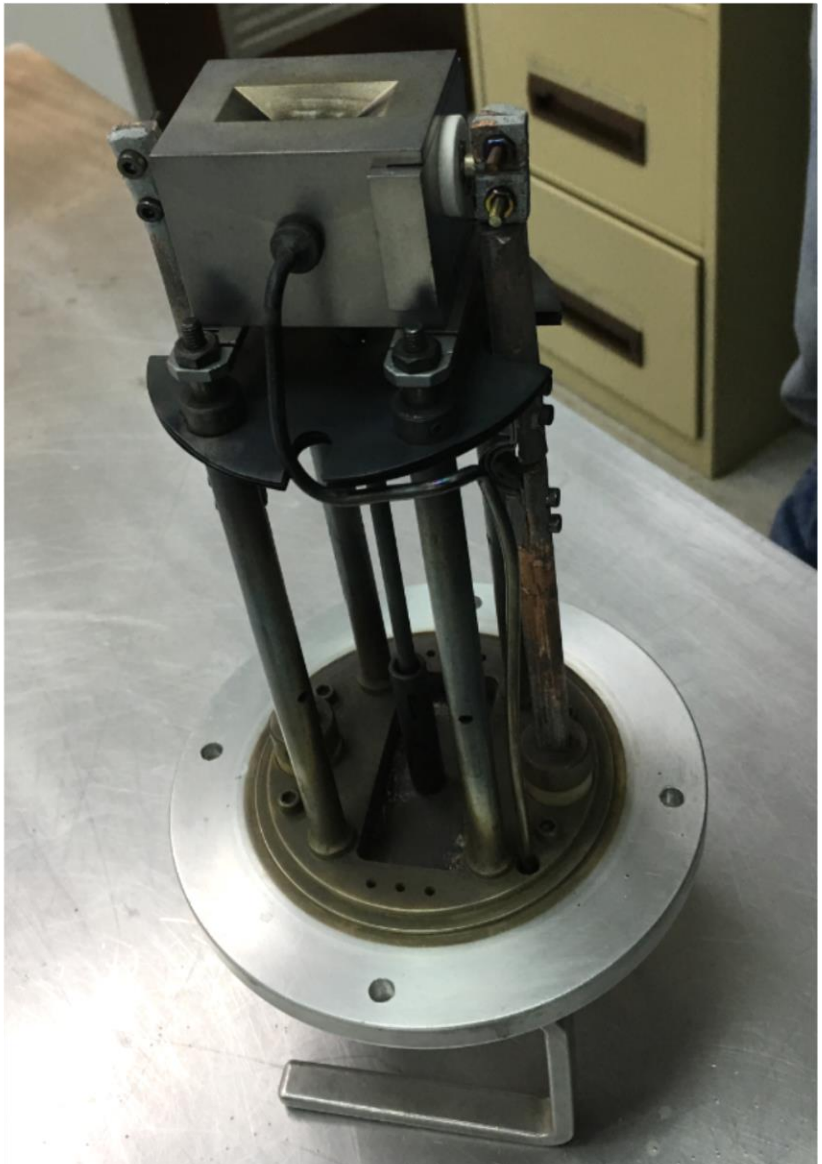
The critical component in the Freeman ion source is the externally heated hot filament (ion source filament was estimated to be in range of 2400 to 2500 K) that drives the arc discharge. It is a straight tungsten wire placed parallel to and close to the extraction slit. The intense filament mass erosion processes limit the ion source lifetime: thermal evaporation and sputtering. Sputtering rate is several magnitude of order higher than the thermal evaporation rate.

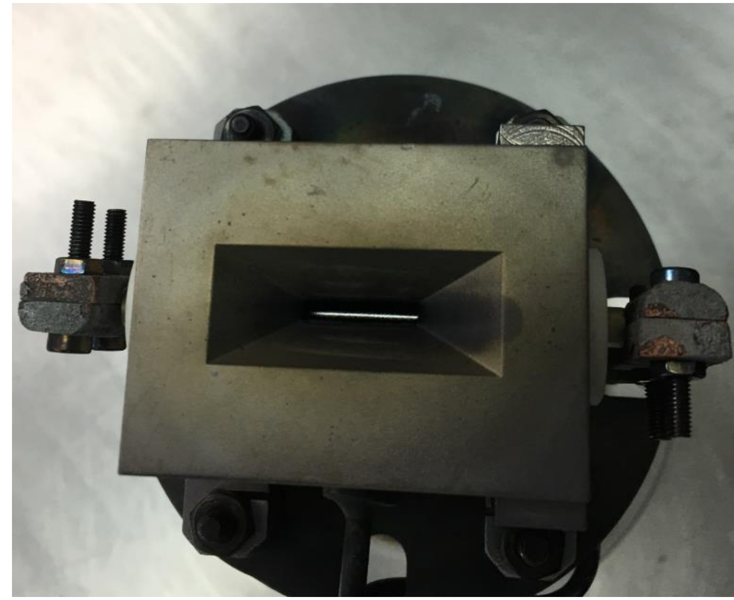
Main characteristics of the Freeman ion source:

- High beam current outputs (mA).
- Uniform beam profile over the long beam extraction slit to obtain high quality beam at the end target.
- Plasma regime free from high frequency electrical oscillations.

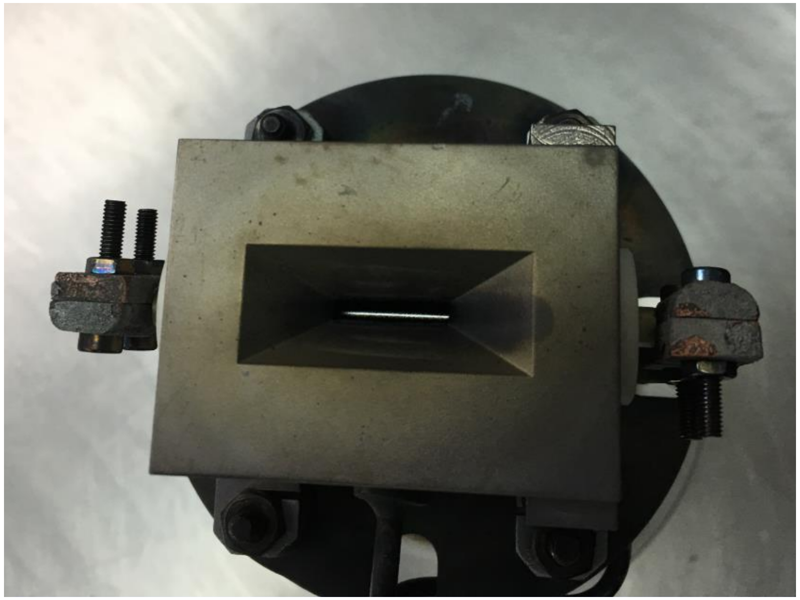
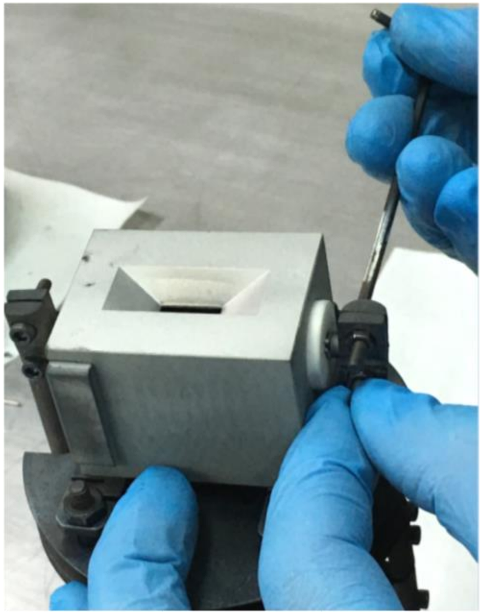
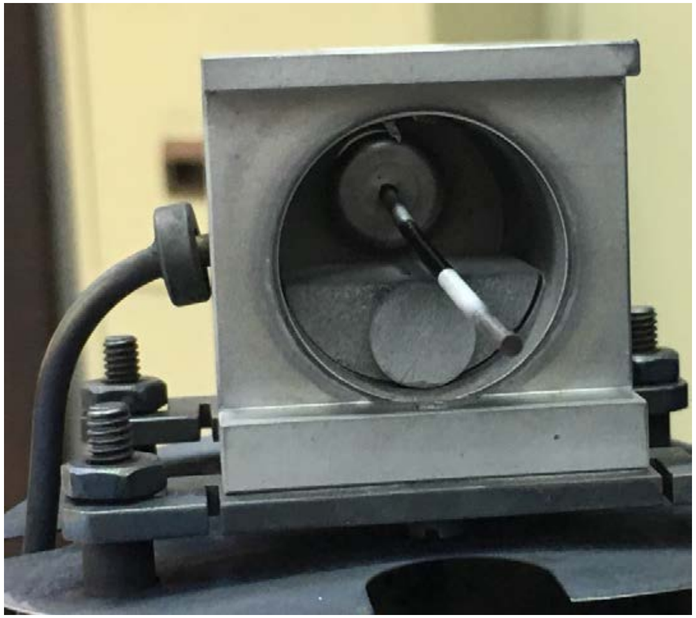
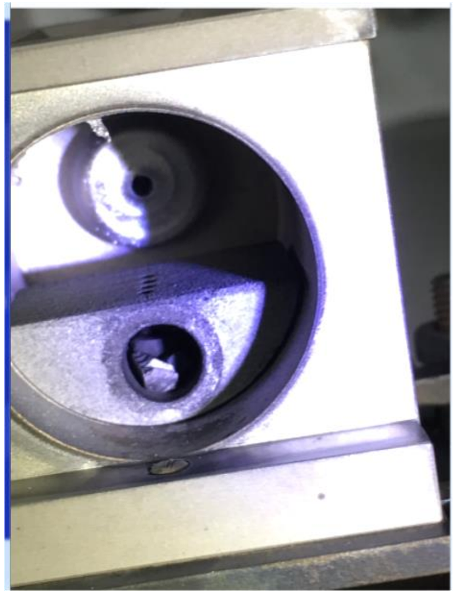
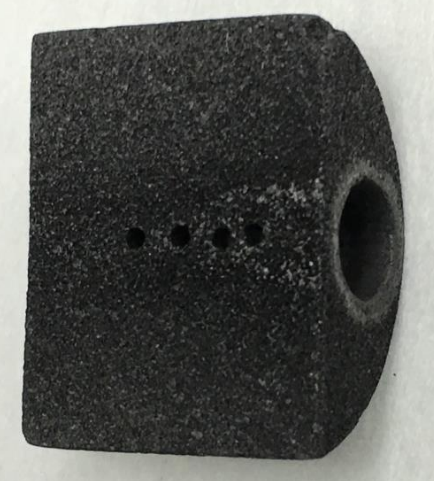
Hot Filament Performance in a Freeman Ion Source Ilija N. Draganic et al
Proceedings of the 17th International Conference on Ion SourcesAIP Conf. Proc. 2011, 030005-1–030005-3; https://doi.org/10.1063/1.5053266

Freeman ion source for ion implanter at iThemba LABS





Freeman ion source at iThemba LABS

Radio Frequency (RF) Ion Source

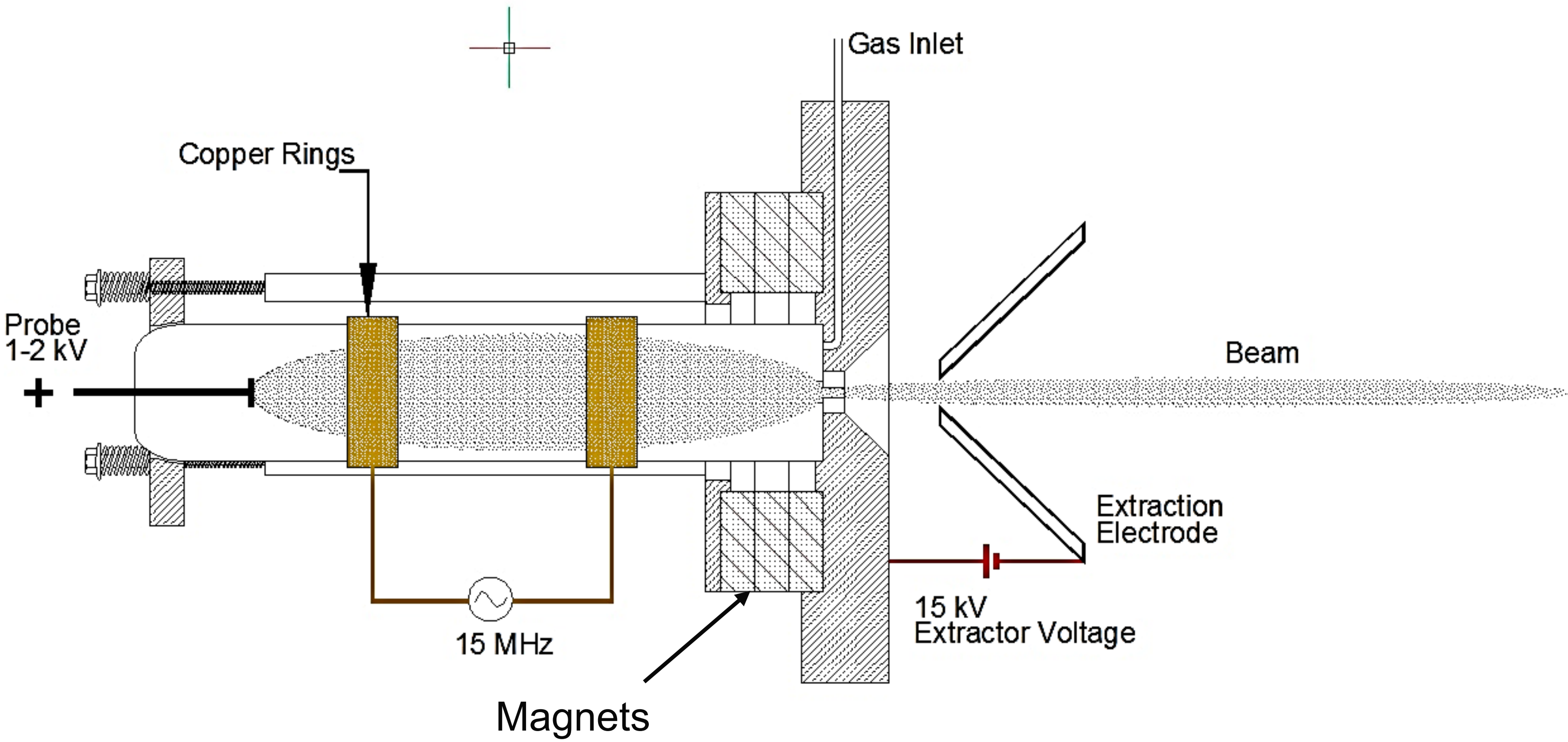
- 1940: using rf voltage to create a plasma
- can operate with any type of background gas
- useful for long-life operation and clean plasma production
- used by the semiconductor industry

Radio Frequency (RF) ion source

In practice, an RF discharge is formed in a vacuum vessel filled with a gas at a pressure of about 10^{-3} to 10^{-2} Torr. To establish a suitable discharge, a few hundred watts of RF power is required. The RF frequency can vary from a mega-hertz to tens of megahertz. A low-pressure gas can be excited by RF voltages using two ways:

- Capacitively coupled discharge in which a discharge between two parallel plates across which is applied an alternating potential.
- Inductively coupled discharge in which a discharge generated by an induction coil. Most RF ion sources are operated with this type of discharge. It consists of a quartz discharge chamber to reduce recombination at the inside surface of the vessel surrounded by the RF induction coil from the outside. There are four external variables that affect the character of the discharge and the resulting ion beam such as; the gas pressure in the chamber, the magnitude and coupling to the plasma of the RF field, the external magnetic field and the extraction voltage.

Radio Frequency ion source (RF)



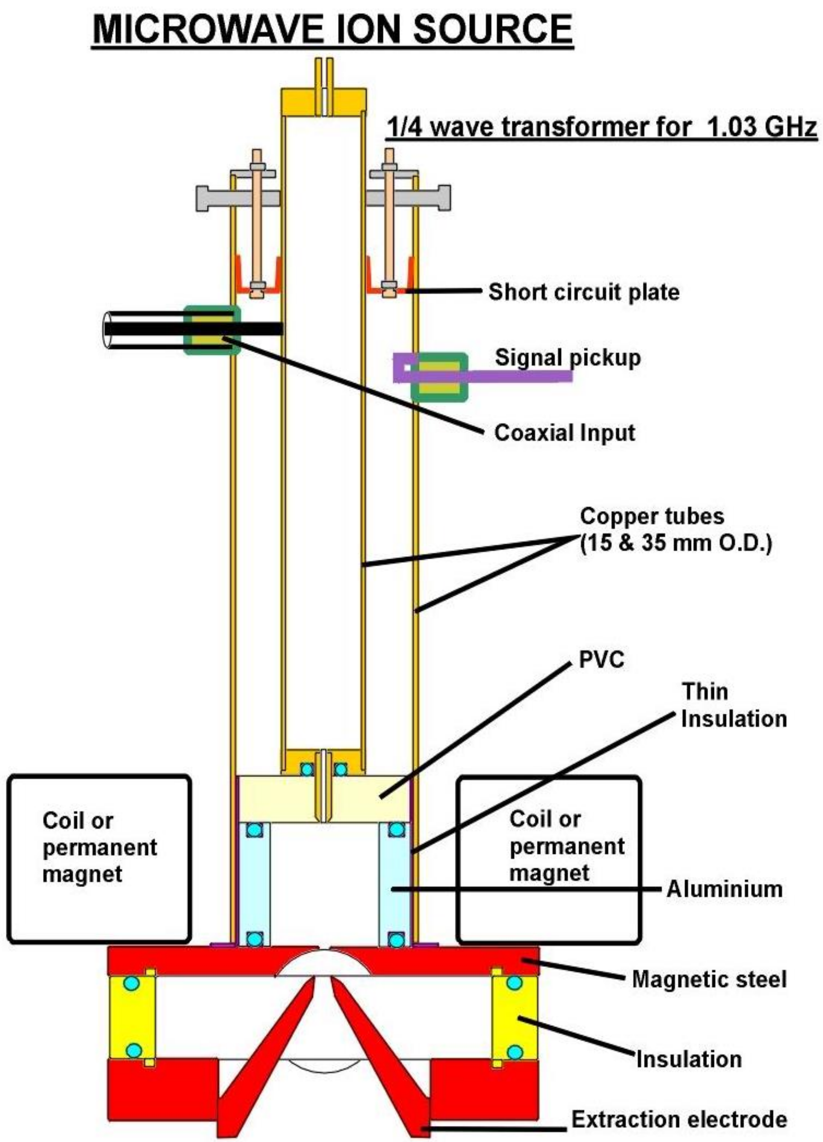
Microwave Ion Sources

Dens plasmas can also be generated by microwave discharges in a magnetic field. In this way filament breakdown and replacement is avoided. Microwave sources can be classified into two types.

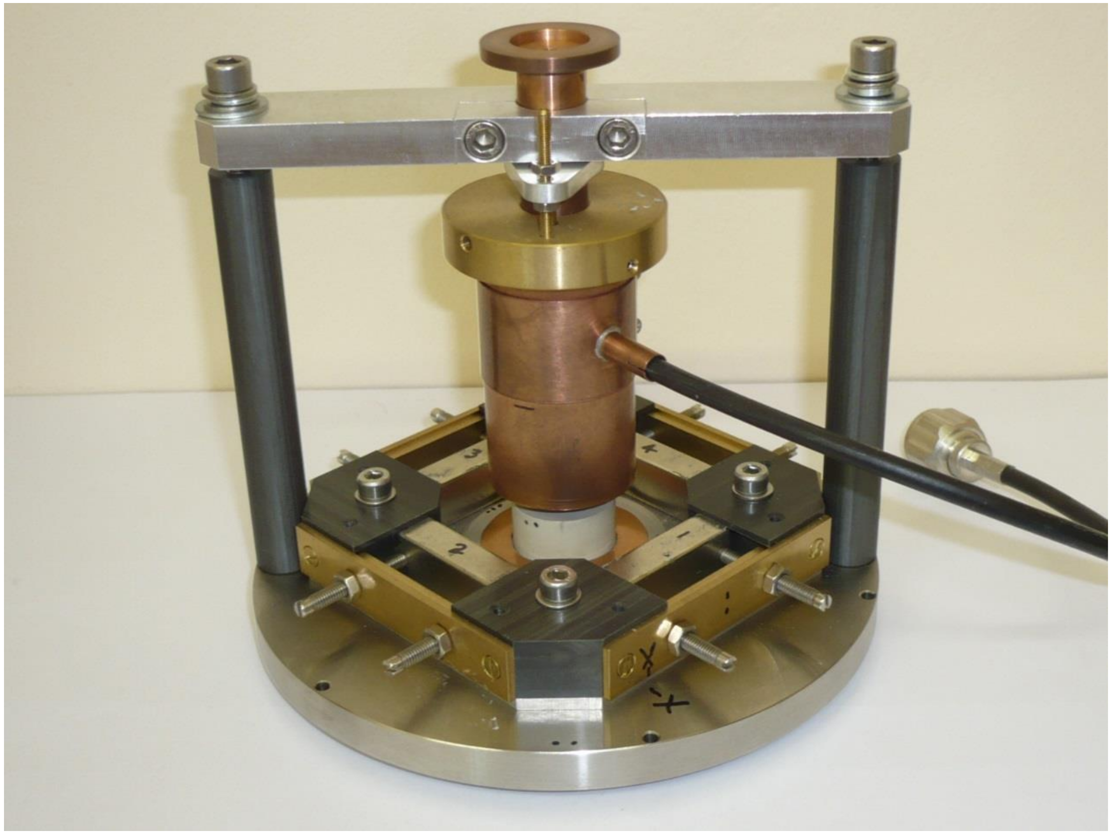
1) One is operated at the electron cyclotron resonance (ECR) to obtain, in a low pressure regime, multiple-charged ions.

2) The other uses off-resonance microwave plasma in the 10^{-1} to 10^{1} pascal range to obtain high currents of singly-charged ions. The extractable ion-current density is proportional to the product of electron density and the square root of the electron temperature. These parameters can be raised by increasing the absorbed microwave power. Microwave ion sources provide ion beams of higher current and smaller energy dispersion than rf ion sources since ions in the plasma are not accelerated by a microwave electric field as they may be in an rf electric field Microwave ion sources can produce mA beams of any species, finding applications in ion implantation devices. The absence of antennas made this type of ion source more reliable for long-time operations.

Microwave ion source at iThemba LABS



Microwave ion source at iThemba LABS



Operation Parameters:

Frequency: 1.265GHz,

Magnetic Induction: 0.08T

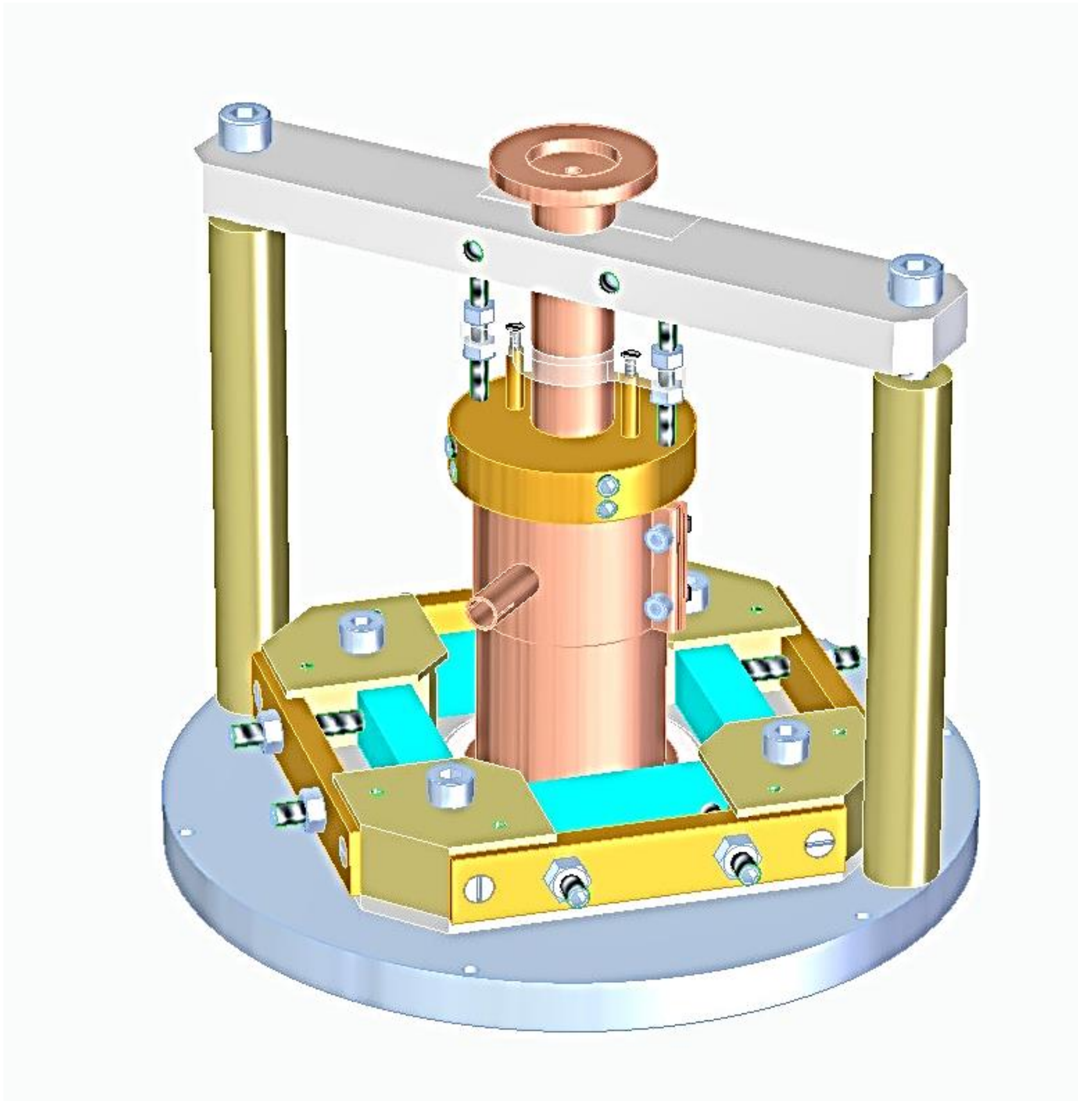
Gas Consumption: 0.06sccm for 0.2mm aperture diameter, 30 weeks, 1l container, 17bar

Extraction Voltage: 3kV

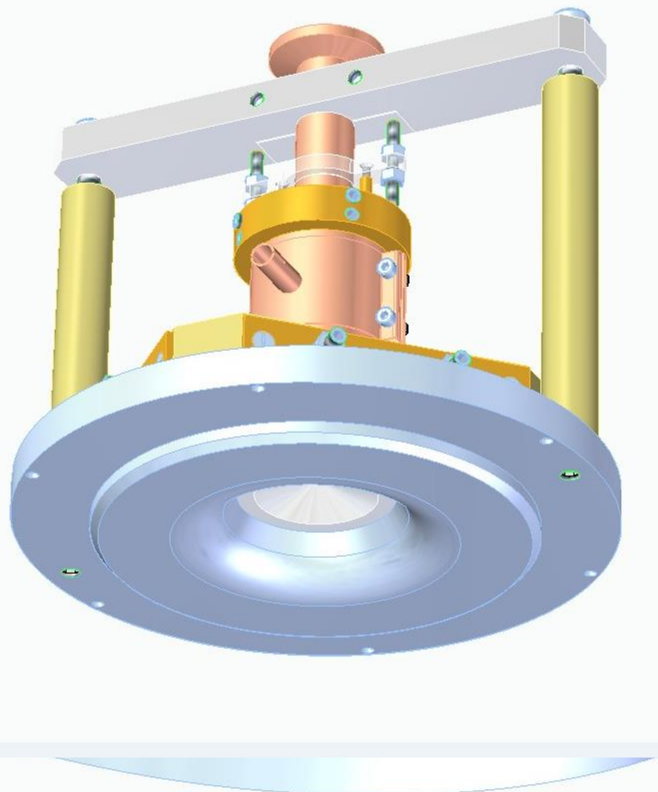
RF Power: 7-10W

No source cooling necessary

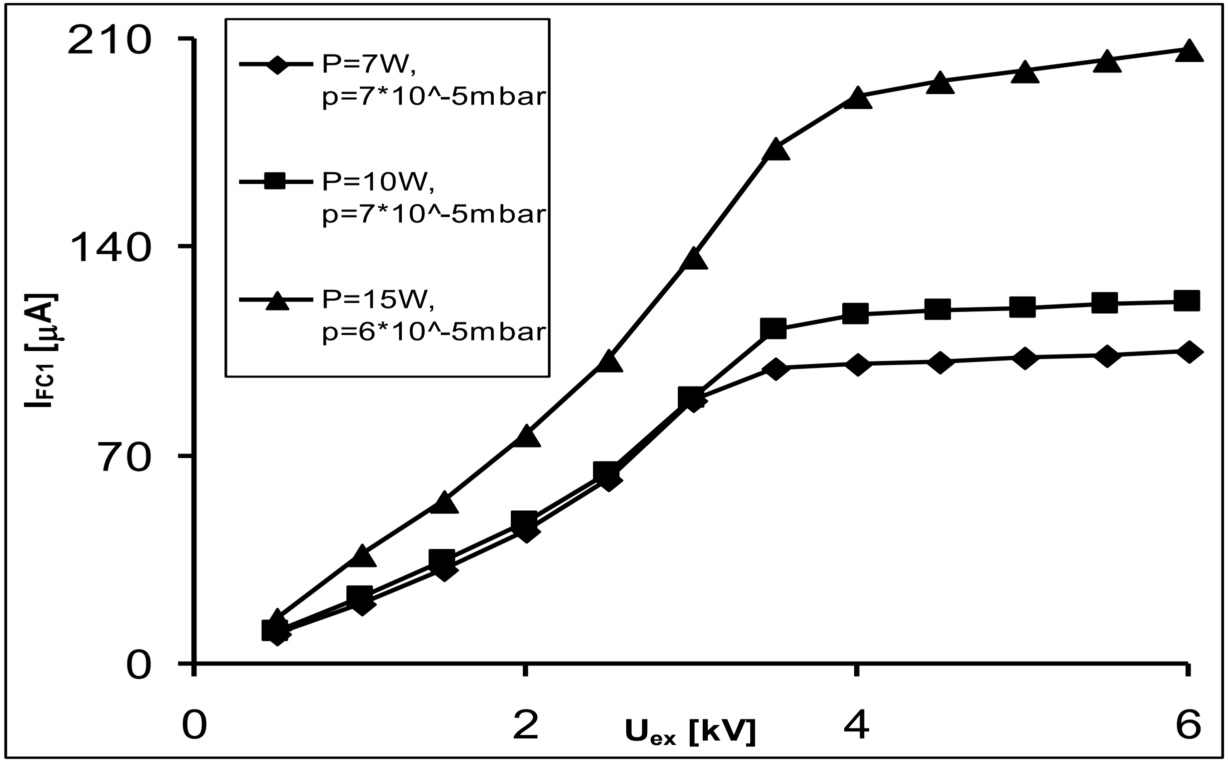
Accelerated current: 10μA H^+, 6 μA He^+, no pulsed operation tested, $H^+/(H^+ + H_2^+ + H_3^+)$=60-80%



Construction of the iThemba LABS microwave ion source



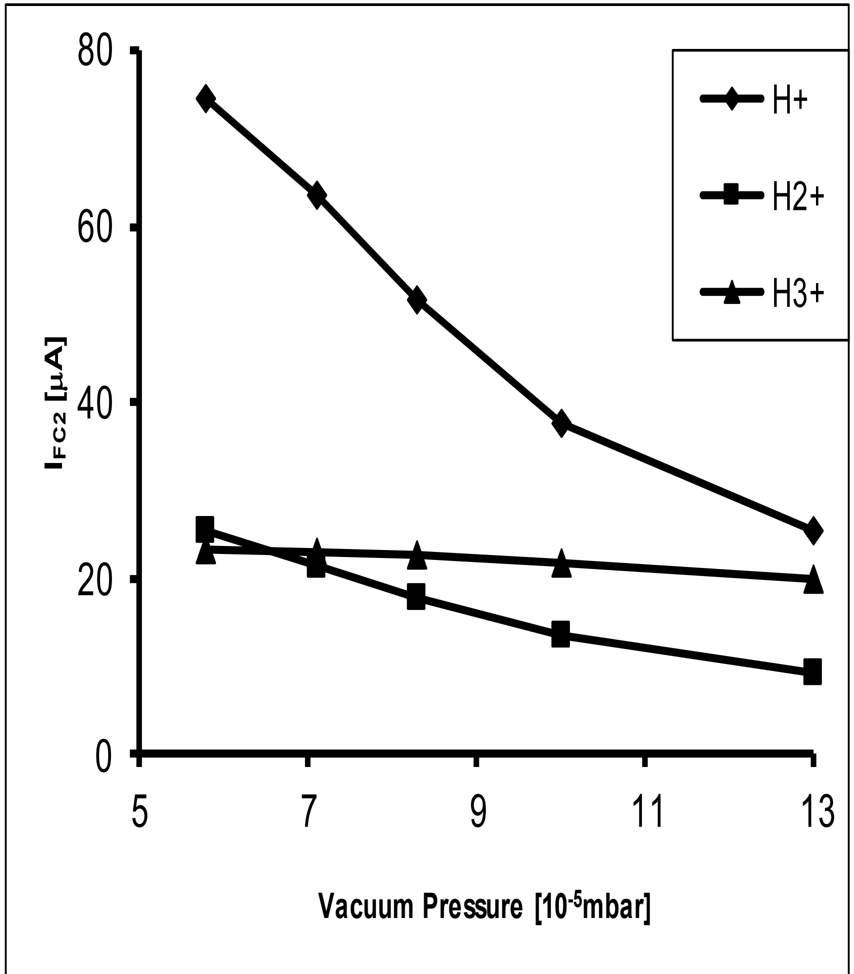
Beam current as a function of the extraction voltage for iThemba LABS microwave ion source



The beam current as a function of the extraction voltage for input powers of P = 7 W, 10 W, or 15 W. At higher input power the H2 gas pressure can be reduced to a lower value without loosing the plasma resulting in a higher extracted current.

The increase in current as a function of extraction voltage follows the Child-Langmuir-Law in between +/- 5 % up to 4 kV (for an outlet aperture diameter of 1.5 mm and a gap distance of 11 mm).

Beam current as a function of the vacuum pressure for iThemba LABS microwave ion source



In A the different species of Hydrogen ions as a function of vacuum pressure are shown.

Electron-cyclotron-resonance (ECR) ion source:

- The electron-cyclotron resonance (ECR) ion source was conceived by Richard Geller as a means of producing the high ion currents needed for fusion applications
- Later it was discovered that ECR sources were capable of providing highly charged ions as well as high currents of 1^+ ions.
- The basic operating principle of the ECR source is to confine the plasma in a vacuum chamber surrounded by an axial magnetic field produced by **solenoid** and a radial magnetic field produced by a multipole magnet, normally a hexapole magnet. Electrons in the plasma follow circular orbits around the magnetic field lines.
- The time required for an electron to travel around the circumference of the circle is proportional to the charge-to-mass ratio of the electron and the strength of the magnetic field. Therefore electrons always make a specific number of orbits per second–the cyclotron frequency, approximately 2.79 GHz per kiloGauss.
- Introducing microwave power at the cyclotron frequency causes the electrons to speed up, i.e. the electrons gain energy from the microwaves. These electrons collide with residual gas atoms in the vacuum chamber. When the energy of an electron exceeds the ionization energy of an atom, that atom can be ionized in the collision.
- The result is a positively charged ion and two electrons. These two electrons absorb more energy from the rf field and ionize more atoms. The number of electrons and ions increases rapidly after the microwave power is turned on, resulting in a plasma comprised of positively charged atoms and negatively charged electrons.

Cyclotron resonance frequency

$$Magnetic\ force\ F_m = QvB_\perp \quad Centripetal\ force\ F_c = \frac{Mv^2}{R}$$

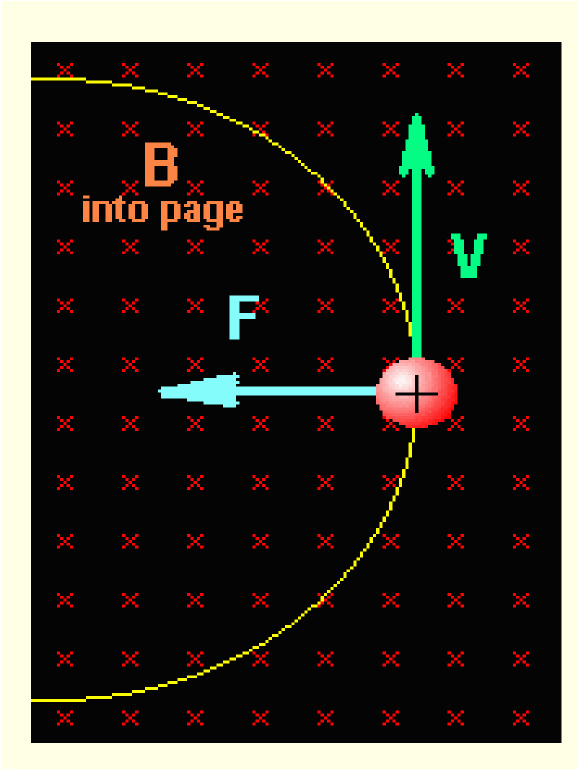
$$\frac{Mv^2}{R} = QvB \Rightarrow \quad v = \frac{QBR}{M}$$

Time for one revolution: $\tau = \frac{2\pi R}{v} = \frac{2\pi M}{QB}$

The frequency $f = \frac{QB}{2\pi M}$

$$f_{ce} = 2.8B \quad \text{GHz}$$

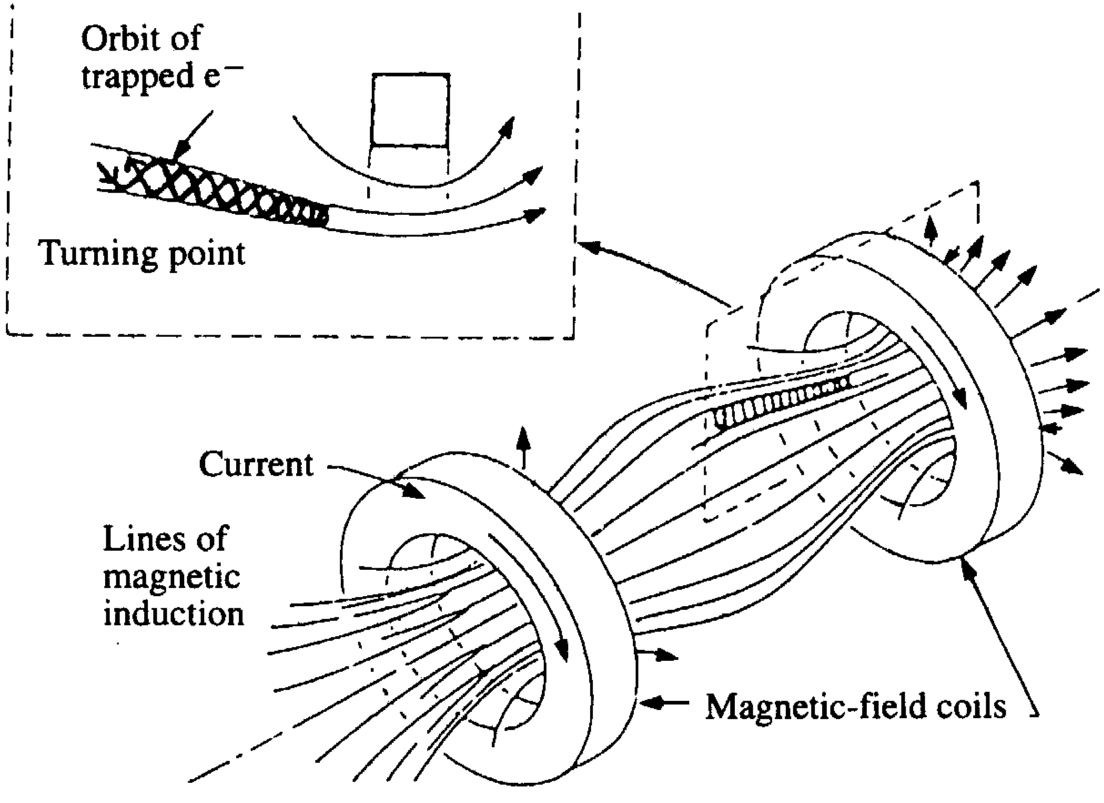
$$f_{ci} = 1.52\frac{Q_n B}{A} \quad \text{MHz}$$



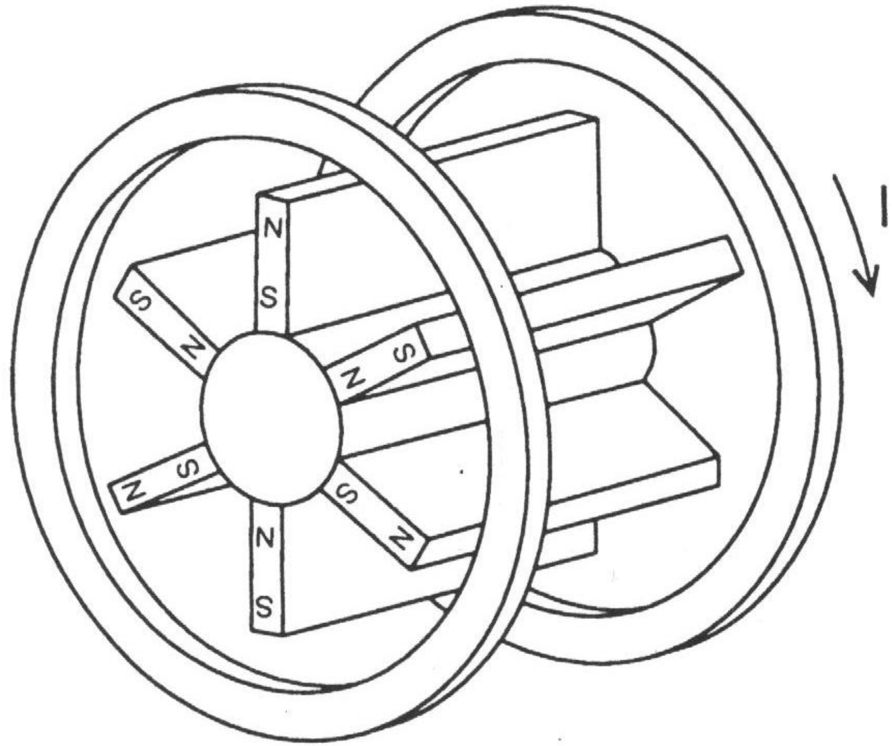
With B in kG and Q_n charge in electron charge units

For magnetic fields of a few kG the electron cyclotron frequency is a few tens of GHz and the ion frequency is typically kHz to a few MHz

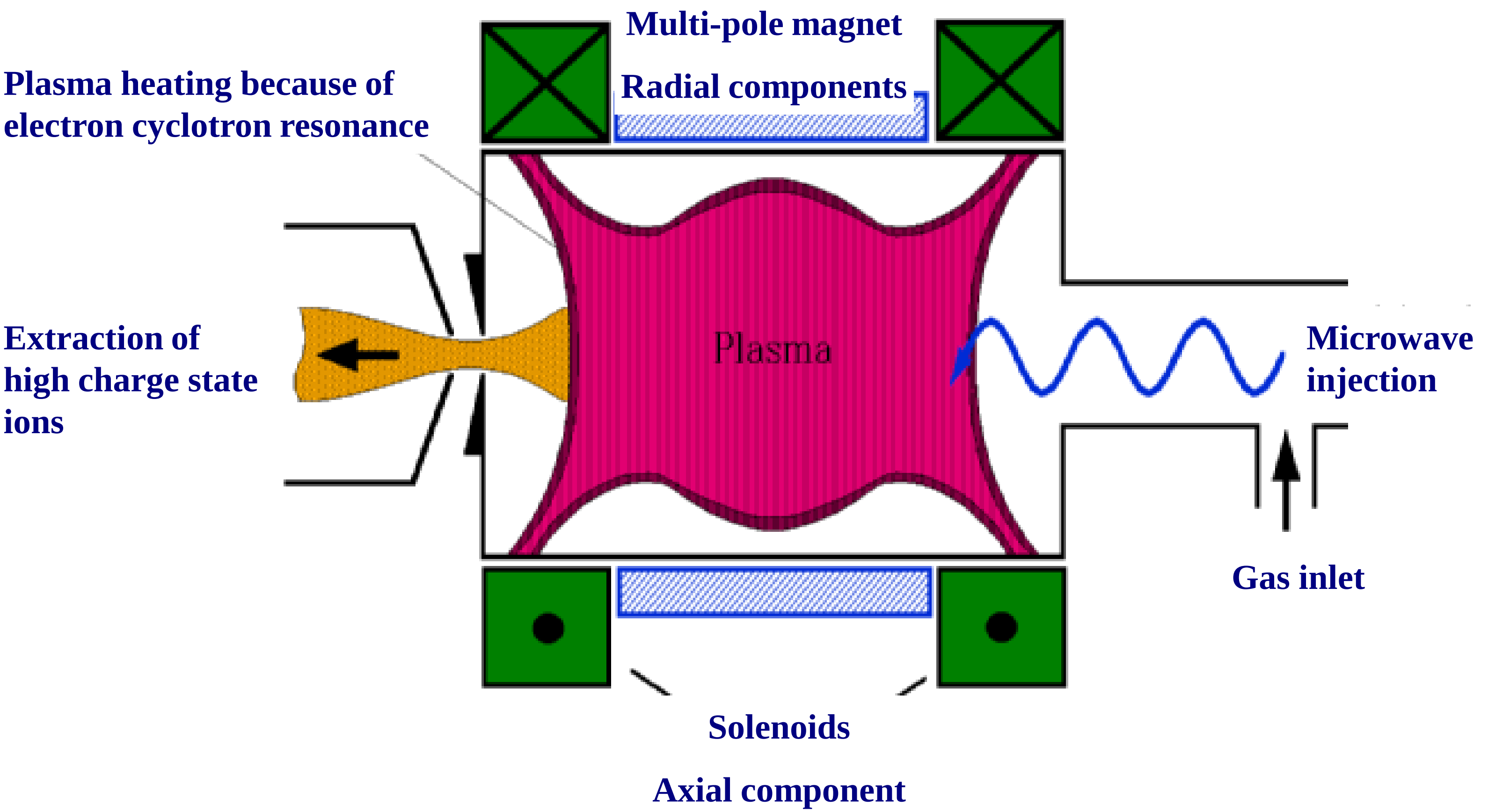
The magnetic ‘mirror’, also called the simple mirror



Coils and a permanent hexapole magnet



Basic principle of ECRIS



CHARACTERISTICS OF ECR ION SOURCES

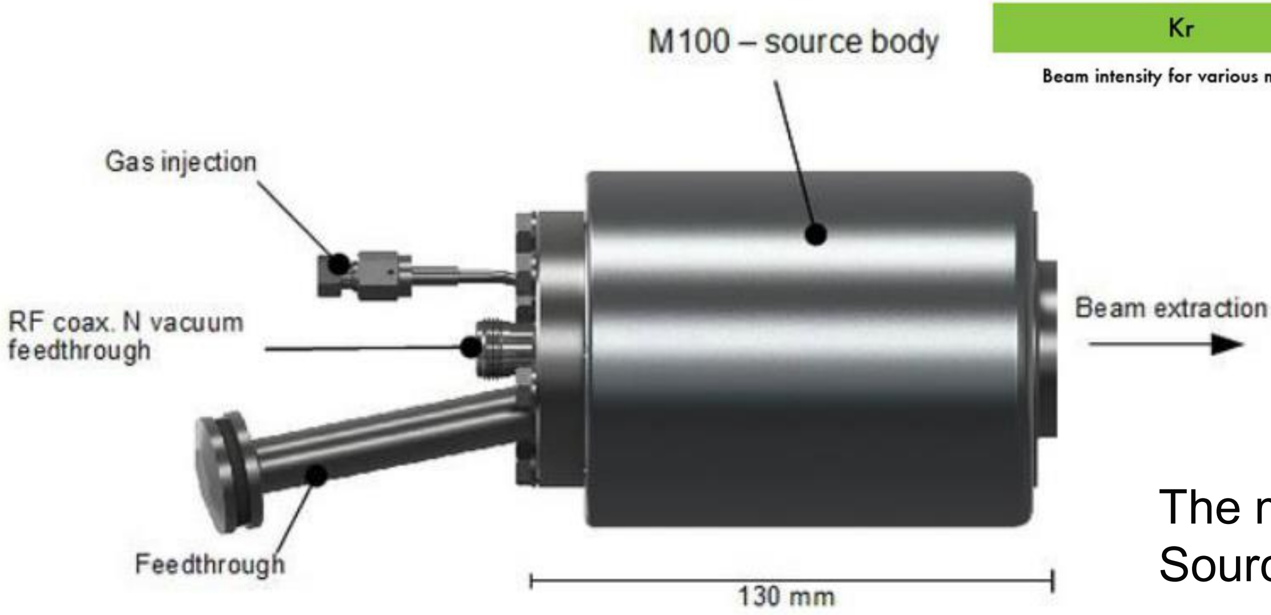
- Because the plasma is contained by magnetic fields instead of electrodes these sources have long life-times and operate reliably - sometimes up to a month without attention.
- A wide ranges of elements, both volatile and non volatile, can be ionized with a low gas consumption.
- Produce heavy ions with very high charge states.
- ECR sources are relatively expensive and large.

ECR ion source from company Pantechnik

Monogan M-100

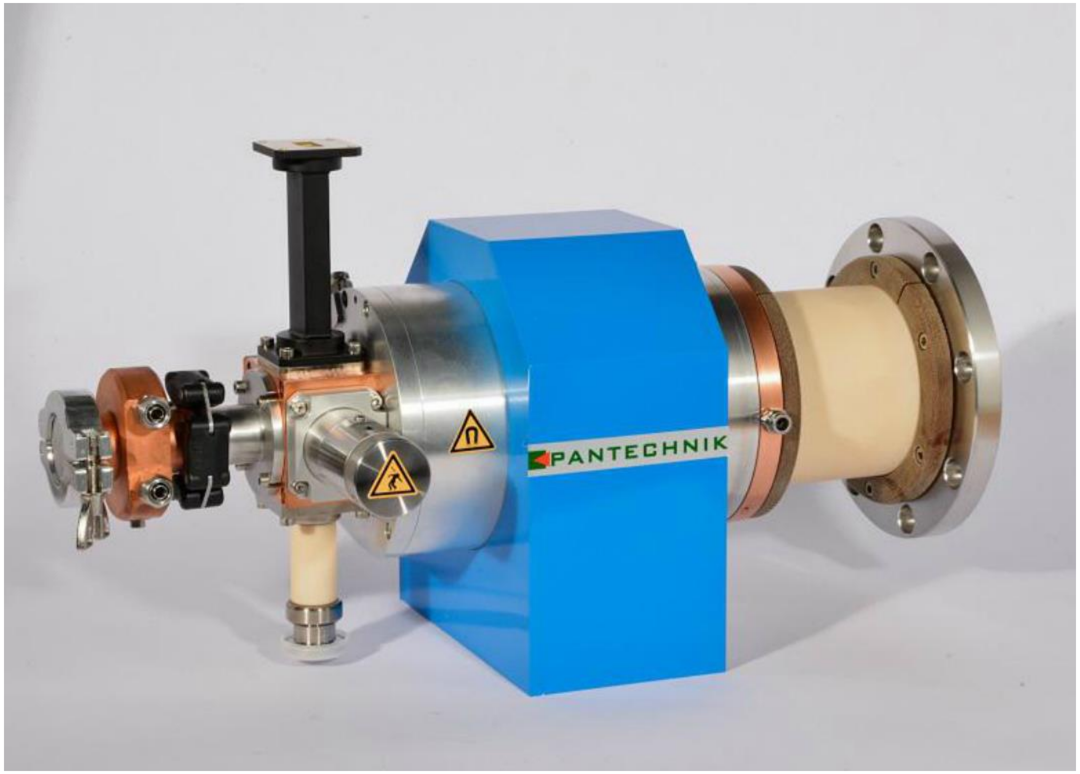
ion / Q = 1	Beam intensity (μA)
H	500
He	1000
N	40
Ne	500
Ar	350
Kr	90

Beam intensity for various mono-charged ions in electric μA (@ 80W RF power)



The most compact ECR Ion Source from the compant

ECR ion source from company Pantechnik

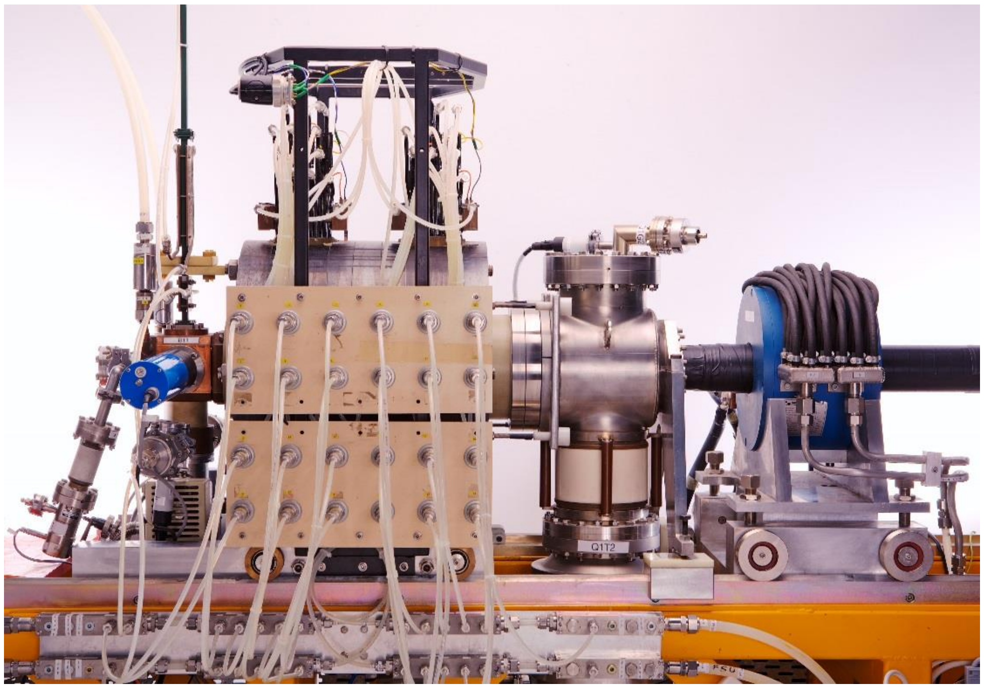


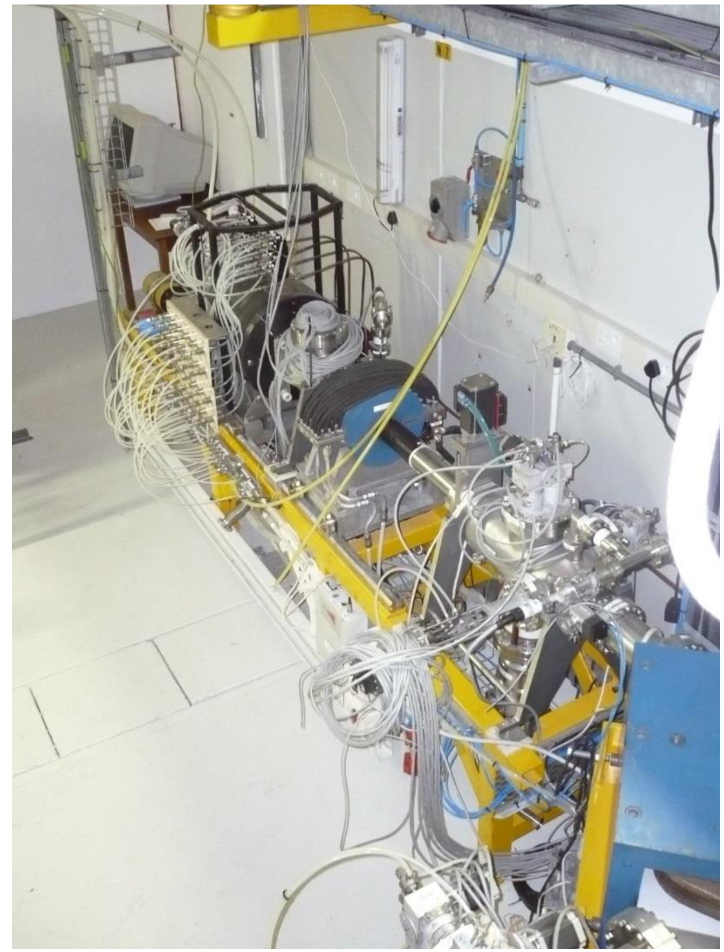
Nanogan 10 GHz - 100W ULTRA COMPACT ideal for electrostatic accelerators

ion / Q	1	2	4	6	8	9	12	14
H	1000							
He	1000	100						
Ar	300		140	45	20	5		
Xe							10	5
Ta					10		10	5
Au			10	9	8	6		2

Beam intensity for various charge states given in electric μA

HMI ECRIS4 14.5GHz



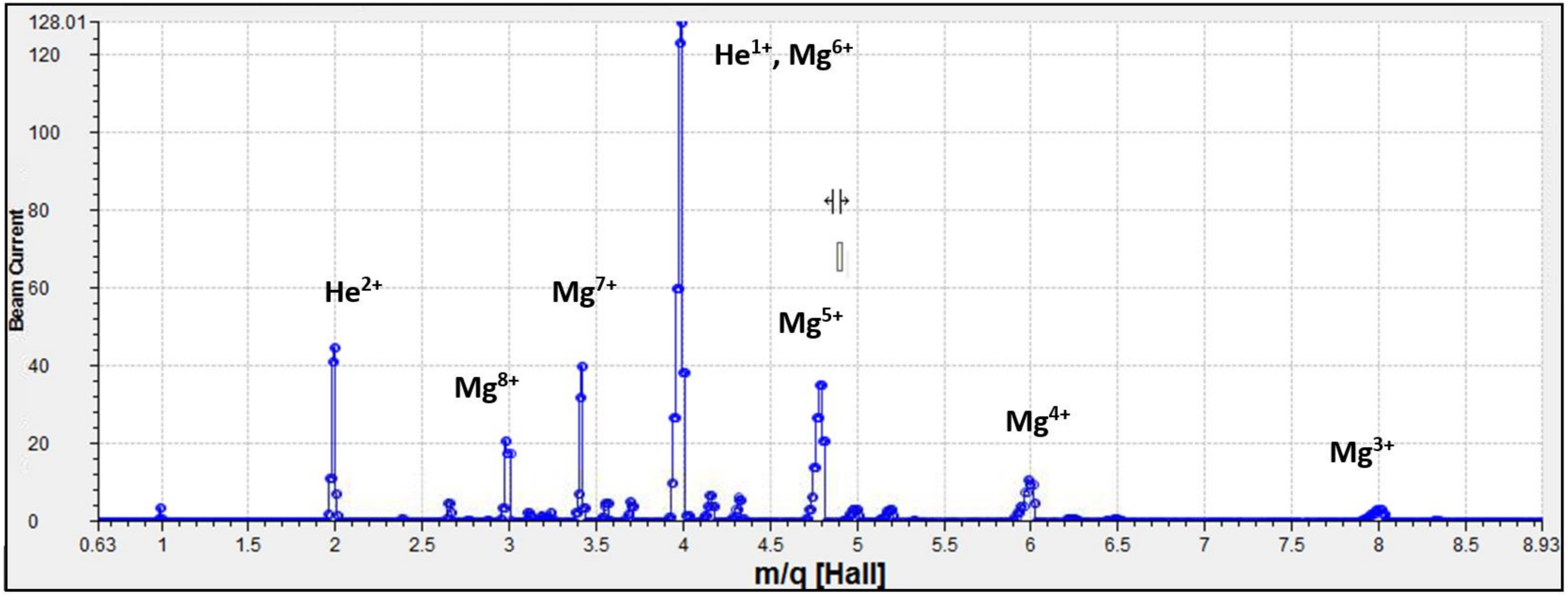


H, He, C, O, Si, Xe, max. 20keV/amu from source, 5-200eμA analyzed beam current

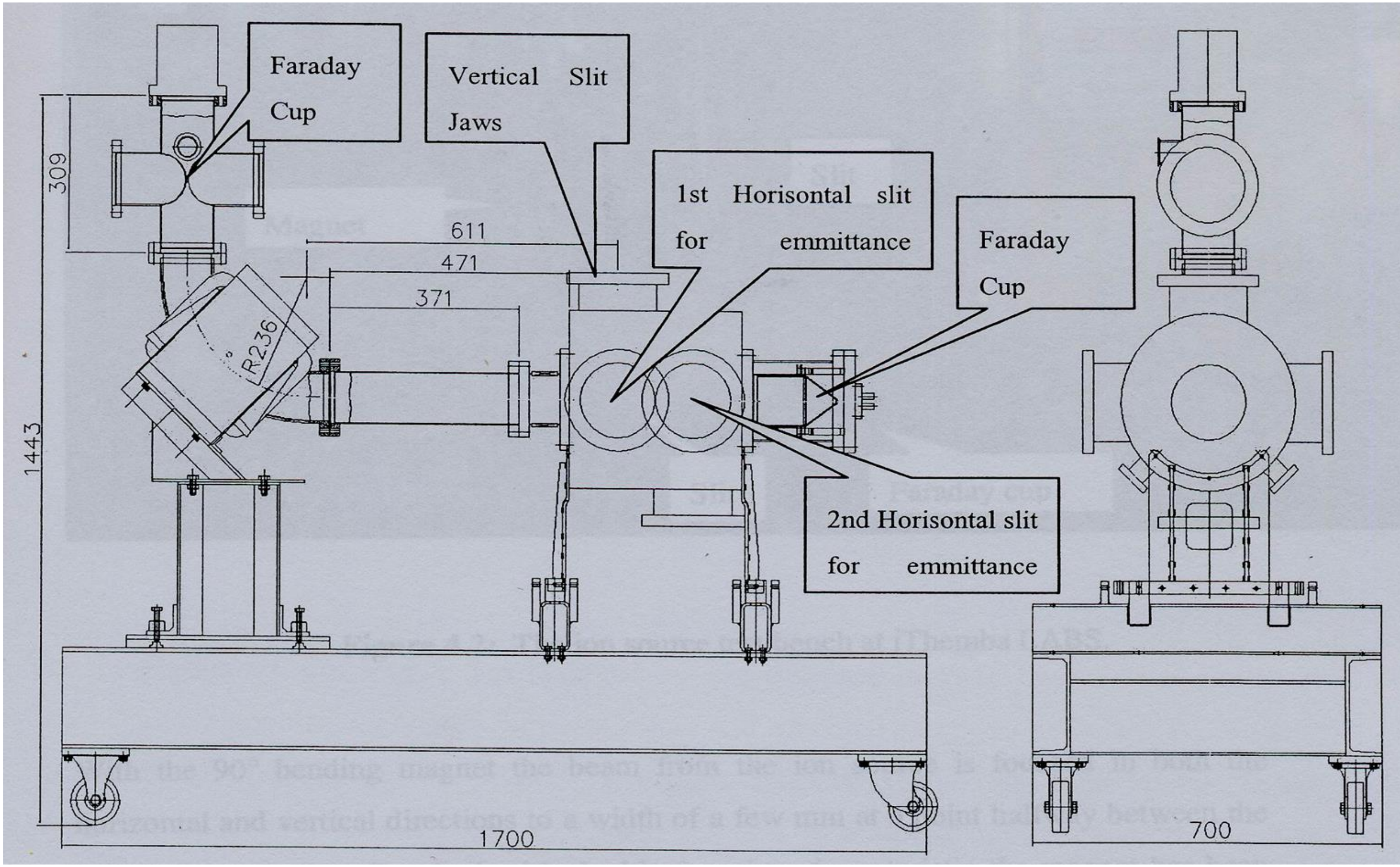
GTS2 14.5 and 18GHz

Element	Maximum Charge State	Current from the source (eμA)	Energy of beam from the SSC (MeV)	Energy per nucleon From the SSC (MeV/u)
Xe	37+	5.4	2335	18.1
Kr	24+	15	1360	16.2
I	27+	10	1100	8.6
Ar	17+	4.2	1590	40

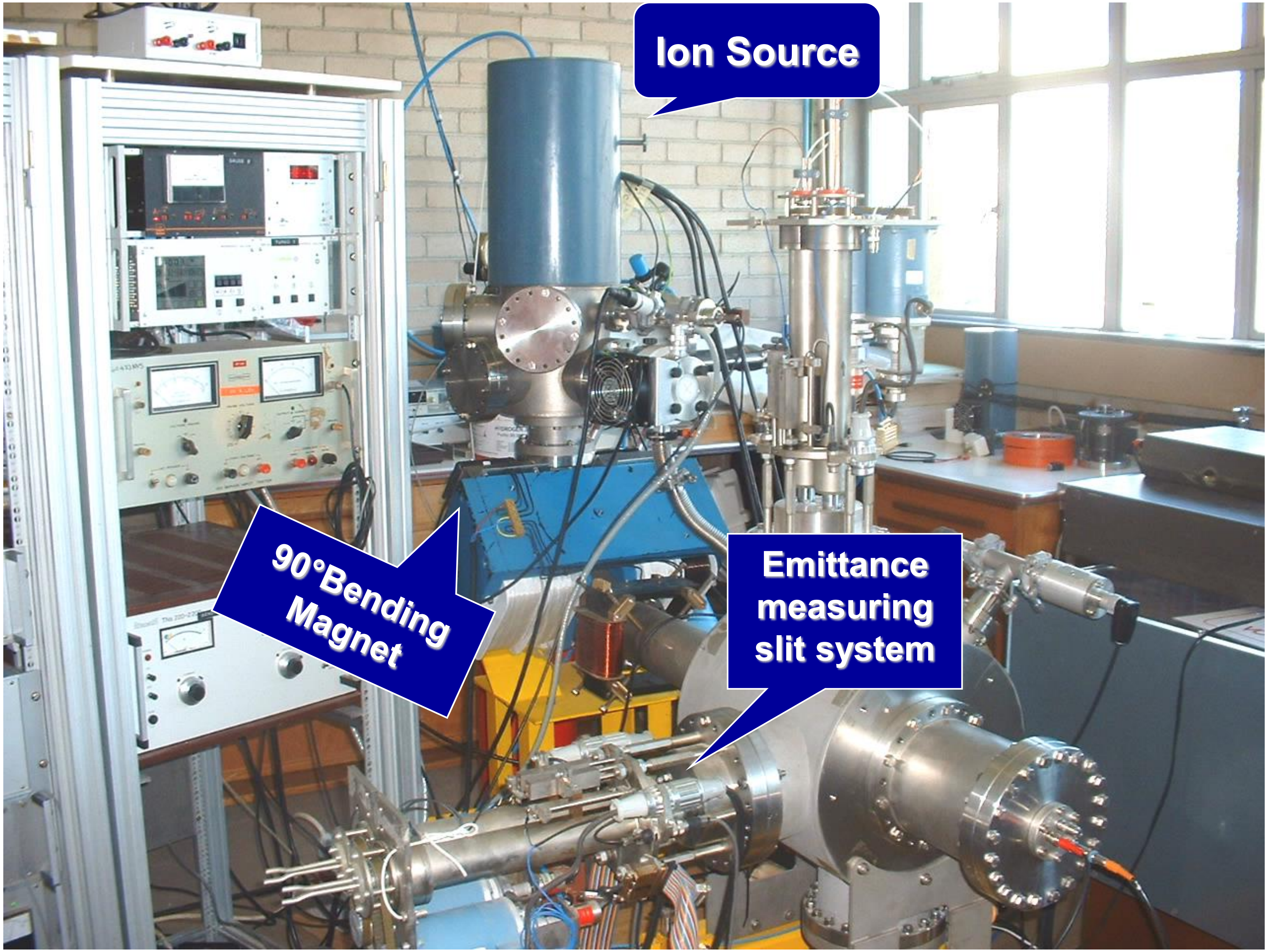
Magnesium oven operation. Spectrum of the extracted ion beam from the source measured behind a104^0-bending magnet on a Faraday cup.



Ion source test bench



Ion Source Test Bench



Thank You