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ELECTRON DONORS AND THEIR ROLE ON THE PERFORMANCE OF MICROWAVE DISCHARGE AND ELECTRON CYCLOTRON RESONANCE ION SOURCES

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Abstract

In order to enhance the output of highly charged ions from an electron cyclotron resonance ion source (ECRIS), several techniques like wall coating, biased disk, electron gun have been proposed and are meanwhile employed as standard tools at most of the existing installations. Although the detailed mechanisms are not clear, it has become evident that the additional injection of electrons into the plasma chamber of an ECRIS considerably improves its performances. Depending on the special conditions of the source these additional electrons can either compensate for losses of plasma electrons or even may change global plasma parameters (e.g. plasma potential) and hence positively influence the extraction at high rates of highly charged ions. The first experiments on biased disk were carried out at CEA, Grenoble and KVI, Groningen in 1990-91 and since then, this method is used by almost any ECRIS in the world. Wall coating is not so widely used but it has been proved to be effective not only for ECRIS but also for microwave discharge ion source (MDIS). Other methods to provide electrons to the plasma will be described in the following. In particular, at the Institute of Physics and Nuclear Engineering (IFIN-HH), Bucharest, special metal-dielectric (MD) structures of Al-Al_2O_3 have been developed. They are characterized by their very high secondary electron emission coefficients and therefore they seem to be ideal to be used in an ECRIS. Preliminary tests at IK in Frankfurt and at KVI have given interesting results. In the following an analysis of the possibilities opened by this method and other methods involving electron donors in ECRIS and MDIS field is carried out.

1 – Introduction

Electron Cyclotron Resonance ion source (ECRIS) operating principle [1-8] relies on the following principle: a plasma is produced in a chamber at low pressure (10^{-6}-10^{-8} mbar) in presence of a confining magnetic field B, by means of microwave field. When the confining magnetic field B matches the cyclotron resonance condition for electrons i.e.

$$B = B_{ECR} = 2\pi f \, m/e \qquad (1)$$

(where f is the frequency of the microwave) over a closed surface inside the chamber, the electrons are accelerated by the microwave field [1]. The interaction of energetic electrons with neutrals and low charged ions leads to a sequential ionisation and to the production of highly charged ions (HCI). A general description of an ECRIS is shown in fig. 1.

The electron population in the ECRIS plasma has a broad energy distribution, to which correspond a temperature T_e increasing with the rf power P_{rf} and with the electron confinement time (the longer the electrons stay in the plasma, the larger the energy increase as well as the probability to interact with ions). The electron confinement time τ_e affects the ion confinement time τ_i, which order of magnitude is about the same.

The third fundamental parameter of the ECRIS plasma is the electron density in the plasma n_e, which approaches a cut-off value n_{utoff} as soon as the magnetic field increases (saturating for values higher than twice the resonance field B_{ECR} inside the chamber). A complete explanation of the so-called ECRIS Standard Model is available in [1-8]. The charge state distribution (CSD) of the produced ions, as suggested by the experience, depends on the ion lifetime τ_i (to which the mean charge state <q> is related), on the plasma electron density n_e that determines the beam intensity, and on the electron temperature T_e. The electron density n_e and the ion lifetime τ_i can be multiplied each other to form the quality factor $QF = n_e\tau_i$ [3] which determines <q> along with the electrons temperature T_e, as <q> increases when both increase [4].

In fig. 2 the ionisation capability is plotted vs. the electron temperature and the quality factor. It is clearly shown that a significant increase of <q> can be obtained only through a large increase of the quality factor. As example, an order of magnitude higher QF is required to obtain bare Argon ions than Oxygen ions; that can be accomplished by increasing the confinement time and frequency by a factor about two for each. This increase is obviously not so easy, involving the availability of complex and expensive magnets in the first case and expensive microwave generators in the second.
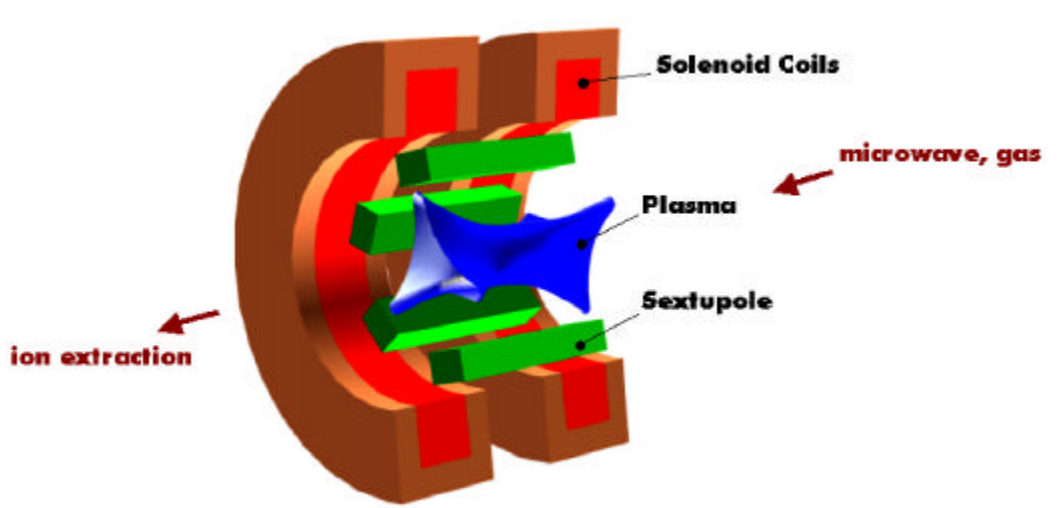
Fig.1 - A schematic description of an ECR ion source [9].

The electron temperature sets the value of the mean charge state <q> of the ion beam as the optimum T_e (needed to achieve a charge state j) is about 3 times the corresponding ionization potential $W^{(j)}_{ion}$ [1].

Fig. 3 shows the ionization potential for all species. As example, the optimum T_e to ionize Ar^{16+} ions is above 3 keV, being $W^{(j)}_{ion}$ equal to 916 eV. According to fig. 2, both conditions must be met, i.e. a value of T_e higher than 3 keV and a QF above $3*10^{10}$ cm^{-3} sec.

All these parameters are strictly correlated in ECRIS and there is no way to finely tune one of them without affecting the others, being further limited by the availability of rf power. The power is determined by the formula

$$P_{rf} = n_e\, kT_e\, V / \tau_e \qquad\qquad (2)$$

so that a power increase reflects in a T_e increase once that the confinement is good and n_e is equal to $n_{cut\text{-}off}$, otherwise it may even reflects in a τ_e decrease because of instability triggering.
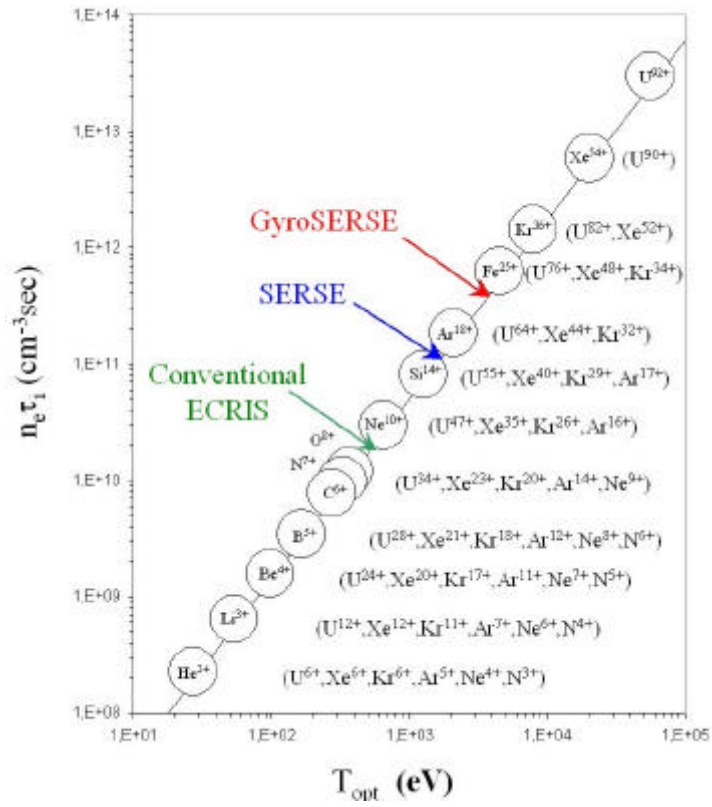
Fig. 2 In the Golovanivski plot the achievable charge state is given in terms of the electron temperature and of the QF.
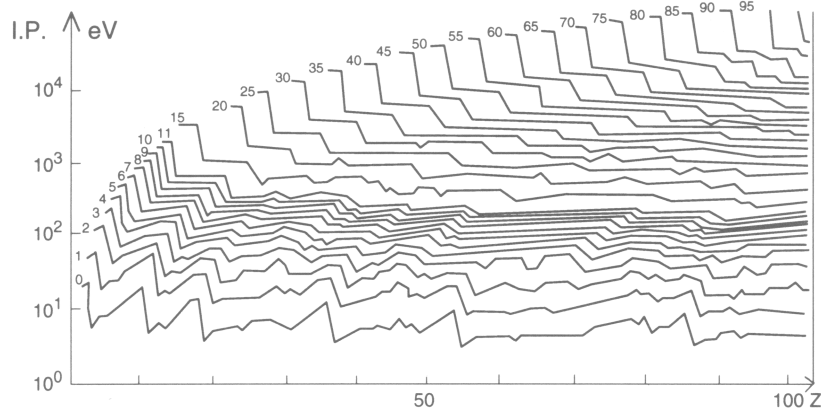

Fig. 3 Ionization potential of element [1]. The atomic number is given on the X axis and the ionisation potential on the Y axis, while the number in the figure indicate the charge multiplicity.
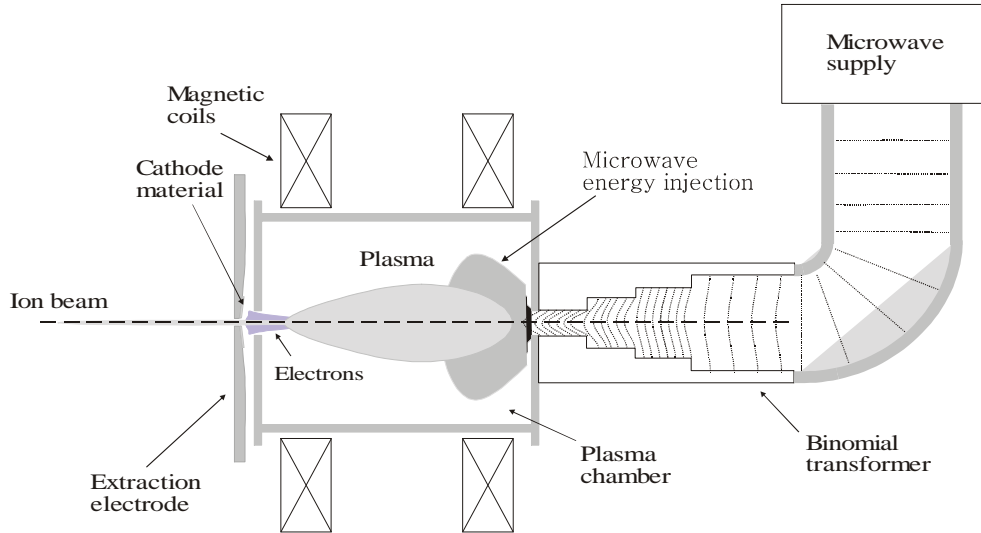
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Figure 4. A sketch of a microwave discharge ion source

1.1 The electron deficit

The produced electrons and ions move everywhere into an ECR plasma, but because of their lighter mass, electrons are faster then ions and tend to escape along the loss cone with a higher rate then the slower ions. This results in an electron deficit which is a serious drawback that shortens the ions lifetime [5]. As a consequence a method that can replace the lost electrons and hence increases the electron density n_e would allow us to overcome this problem (even if the energy content of the plasma is not so high as the optimum one, achievable with an optimum confinement). Many solutions have been proposed in order to increase the electron density and hence lower the plasma potential. All of them affects either the current and sometimes even the CSD. Similarly the n_e increase has been observed in microwave ion sources for monocharged ions [10]. In this case the absence of a B-min structure for the magnetic confinement limits the confinement time and the electron temperature, but the increase of plasma density is not following the constraint of the

$$B^2/2\mu_0 >> n_e\, kT_e \qquad (3)$$

condition which holds for ECRIS [7] and limits its performance.

A microwave discharge ion source (MDIS, see fig. 4) is then the ideal testbench for a systematical study of the different e-donor materials, to be finally applied in ECRIS. For the latter, the performance depend so strictly also upon the vacuum and it is not clear whether a material is good or not until a complete outgasing is performed and test requires a much longer time for ECRIS than for MDIS.

A more complete description of MDIS is presented in [10,11,12,13].

2 - The electron donors in ECRIS and MDIS plasmas

The presence in the ECR plasma of an electron deficit cannot be avoided as the confinement is not perfect otherwise the beam current would be low; in fact to get high currents, τ must be of the order of ms or tens ms as the current increases as τ^{-1}. A too high τ_i boosts the CSD to higher $<q>$ but the current is poor (e.g. the behavior of ECRIS operating at 2.45 GHz [14] in High B mode features maximum currents of a few tens $e\mu A$ only but the CSD is almost comparable to the one achievable by ECRIS operating at higher frequencies).

The need to get higher currents of highly charged ions (HCI) implies that the maximum electron density is reached, being the ion current proportional to n_e/τ_i. On the other way a low value of τ_i is not desirable because the HCI production depends on $n_e\tau_i$, as demonstrated by some experiments which can produce very high currents of low-to-medium charge states, mostly in pulsed mode, but are unable to produce very high charge states or cw beams [15,16]. Therefore the goal of increasing $<q>$ for HCI beams produced by ECRIS is conveniently obtained through the increase of n_e.

The positive plasma potential which shorten the ion lifetime in the plasma and then the ionization rate can be damped by using some 'tricks' to provide electrons.

Different systems have been used through the years, starting with the use of a first stage where plasma is created in a relatively high-pressure region. Later on, the wall coating was successfully applied, followed by other "tricks", some of them being used for a short time (like the e-gun) and some others (wall coating, biased disk, Al chamber) being now used worldwide.

2.1 - Wall coating, e-gun and Al chambers

In 1986 it was observed that SiO_2 or ThO_2 coating increased the intensities of the extracted beams [1]. In fig. 5 the CSD with and without coating are shown; the shape of the CSD does not change significantly and the current increase can be explained in terms of a higher n_e and of a relative decrease of T_e.

The beneficial effect of these materials consists of their action as electron donors. In other words, these materials determines an injection of secondary electrons into the plasma replacing the lost ones, which hits the coated wall surface. As a consequence, all those

materials which have a high heating resistance as well as a low work function, i.e. good cathode materials, could be potentially used for coating walls. Nevertheless, not many materials have been checked for this purpose. In particular, Al_2O_3 has been used because of its long life under the wearing conditions of the plasma environment. Other material have not been effective because of their high outgassing rates.

The injection of cold electrons into the plasma, by using an electron gun, was also tested [17]. The performances of the AECR ion source at Berkeley were about three times better with e-gun and also the average charge state increased slightly, but some difficulties in the tuning of the source were reported. Even in this case the improvements are probably connected with n_e increase, whereas τ_i is unchanged or even slightly decreases. A similar behavior was observed by Zschornack and coworkers at the Technische Universitat of Dresden [18]. Fig. 6 represents the change of source performance without and with the e-gun (5 and 10 mA current).
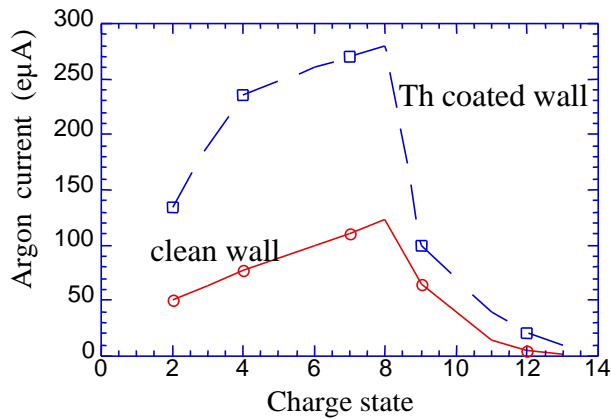

FIGURE 5. The effect of the wall coating [1].

These methods have now been replaced in many cases by the use of Aluminum plasma chambers [19,20]. The Al chamber allows to operate with lower pressure and rf power, thus limiting charge exchange process and plasma instabilities. The creation of a thin oxyde layer works probably as the standard wall coating technique with the advantage of a strong surface versus the wearing process.
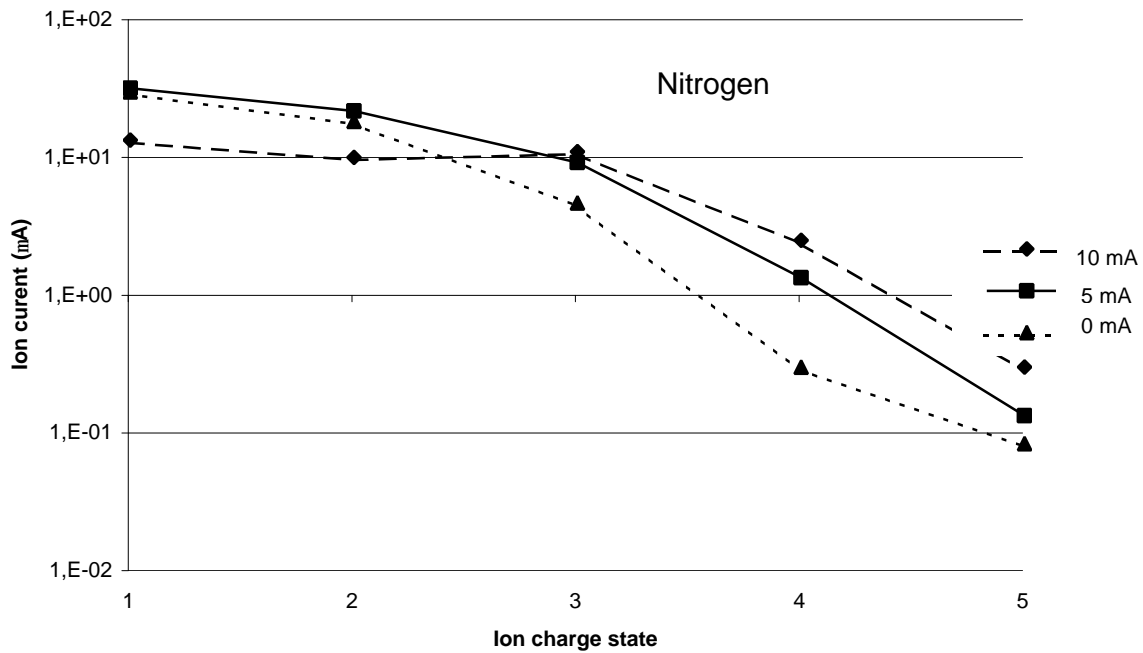
FIGURE 6. The effect of the e-gun in ECRIS [18]; the ion current is given for different electron current (0, 5 , 10 mA) injected in the Dresden ECRIS.

There are some mechanical disadvantages but the advantage in terms of HCI currents increase exceed any cons. It is remarkable that the RIKEN source [19] gave better results with Al chamber and without gas mixing, showing that a quieter plasma is generated. The improvement of the base pressure that can be achieved is very important to minimize charge exchange processes and recombinations in the plasma or in the extraction region (it has been widely demonstrated that in order to produce He-like or H-like light ions an operational pressure of few 10^{-7} mbar, or better, is needed).

2.2 - Biased disk and secondary electron emission

In 1990 it was observed in Grenoble that the presence of a 180 V negatively biased disk inside the plasma chamber improves the source performance [21]. Shortly after a similar experiment was repeated at K.V.I. in Groningen [22], demonstrating that the presence of a -600 V biased disk in the plasma chamber is even more effective. This effect was interpreted as an electron density rise affecting the intensities rather than the CSD.
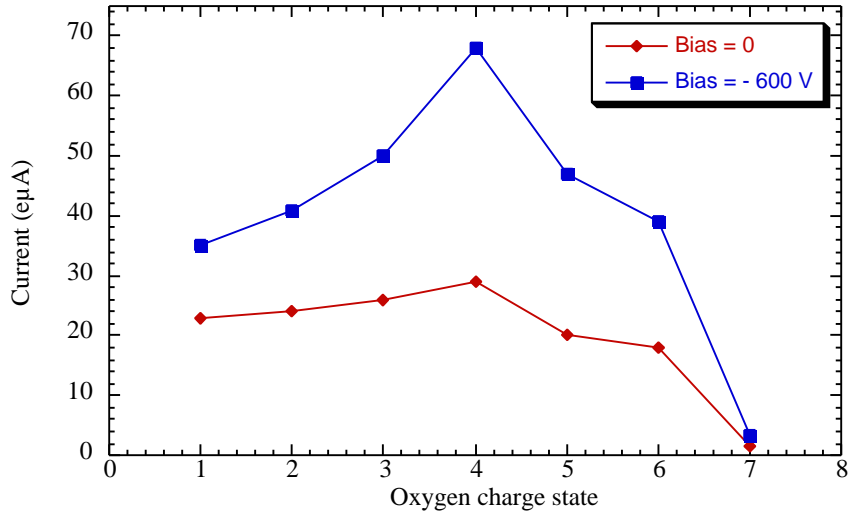
Fig.7 Oxygen currents with and without the bias [22].

In fig. 7 the comparison between the CSD for oxygen with and without the bias have shown that the plasma confinement is almost not modified (even if the source stability is improved, which made easier the optimization of the highest charge states). Then the intensity increased for each state because of higher electron density.

Extensive measurements were carried out at MSU-NSCL in 1994 [23] and saturation effects for O^{3+} were evident for -100 V, because for this value the injected electrons have such energy that O^{3+} ionisation is already optimised (W_{ion} is 55 eV for O^{3+}), while the O^{7+} production (W_{ion} is 739 eV for O^{7+}) is not saturated even at -600 V. Unfortunately, it is not useful to increase the bias indefinitely because more energetic electrons would not be efficiently captured. The effect of the biased disk was systematically measured for different Krypton high charge states, showing a saturation for electron energies above 1000 eV (fig. 8). Anyway the peak current is obtained at V_{bias}=700 V for Kr^{18+}, at V_{bias}=850 V for Kr^{19+}, at V_{bias}=900 V for Kr^{20+} and at V_{bias}=1050 V for Kr^{23+} (W ion 641, 786, 833, 988 eV respectively)

The position of the biased disk and its dimensions need a systematical study for each charge state, as the intercept of the loss trajectories with the disk changes with the position along the axis. We have experienced that there are a few optimum positions but no systematics have been carried out at LNS for position, dimension and metal type up to now; the trend with the voltage confirmed anyway the results of fig. 8.
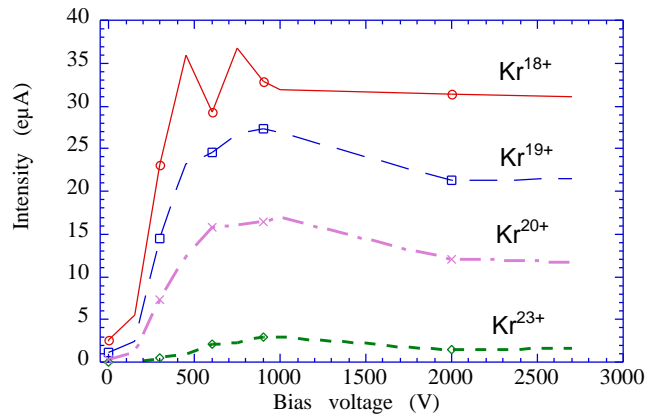
FIGURE 8. Current of medium and high charge states for different value of bias [23].
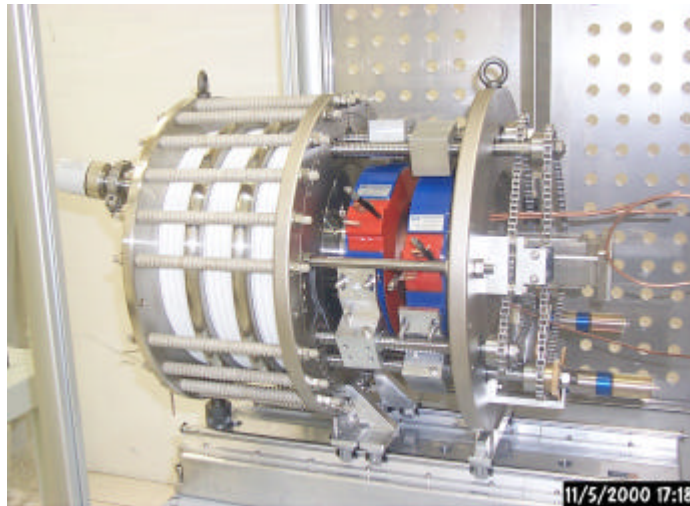

FIGURE 9. The TRIPS source at INFN-LNS.

2.3 - Evidence of electron donors effects in MDIS

The positive effect of electron donors is well known even for MDIS since long time [12]. In fact BN disks are located inside the plasma chamber in different sources [10,12,24,25]
Recently at LNS we tried a new approach by means of Al_2O_3 coating over the extraction electrode of the TRIPS source (fig. 9) as described in [10].
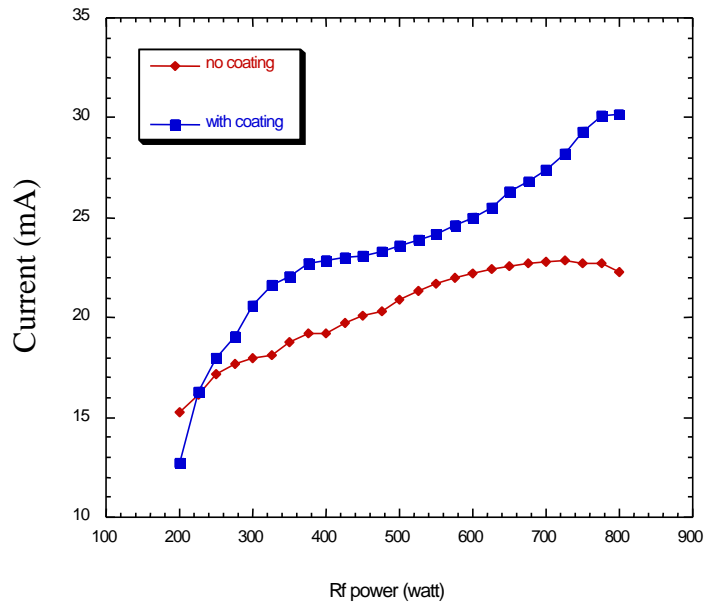
Fig. 10. The proton current increase with power in the TRIPS source with BN disk and with Al_2O_3 coated electrode**.**

The average increase is higher than 30% and it allows obtaining the required current with a smaller extraction hole; unfortunately its long-term reliability is not so good, but tests for a better deposition technique are under consideration.

In fig. 11 the electrode is shown after about 200 hours of operation. Being the emittance and reliability two important requests, the possibility to have this kind of electron donor is appealing and we look for a deposition technique allowing to achieve values of 1000 hours before the performance degrades. A thick Al_2O_3 represents another option to be studied.
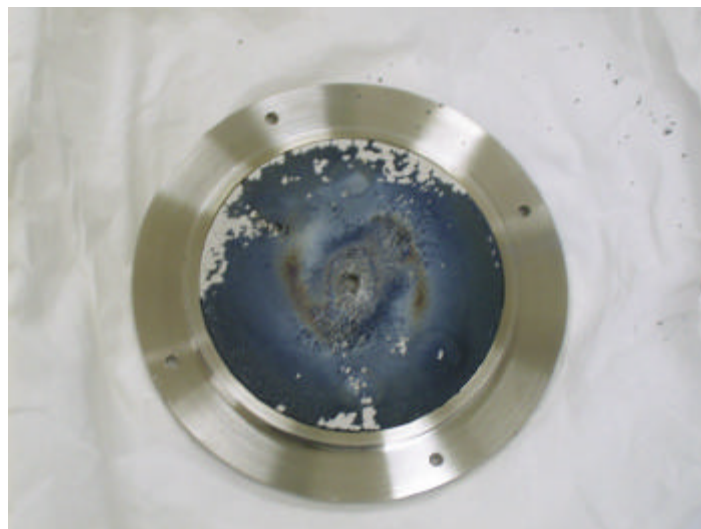

Fig. 11. The coated plasma electrode after three weeks of operation (the Allumina coating which faces the plasma is deposited over the stainless steel electrode with a standard CVD deposition)

3 - Materials studies for new plasma cathodes

In order to have a reliable equipment and to set a reproducible procedure, some general properties must be available for an optimum cathode material:

- Low potential barrier (work function); they should be able to provide an intense electron flow in any plasma condition.
- High melting point and stability at high temperatures, in order to avoid cluster emission and wearing process;
- Low vapour pressure so as to reduce evaporation losses; it is particularly important for ECRIS but it cannot be underestimated for MDIS because they operate usually at high voltage and a too high pressure may trigger a spark.
- Chemical stability, to allow the constant ionisation rate of any species for a long time period.

Efficient cathode materials may be found within metals as well as within compounds, and their pros and cons will be described in the following.

3.1 - Metal elements

Cathode materials exploit thermoionic effect in order to extract electrons underneath a surface because of the thermal energy they gain after heating. By increasing the temperature of our material, an increasing current of electrons is obtained and the emission current density J_c coming out from the cathode is ruled by the Richardson-Fermi law:

$$J_c = AT^2 \exp(-E_w / kT) , \tag{4}$$

where A is the Richardson constant, k is the Boltzmann constant and E_w is the work function of the cathode material.

In order to gain a high current density, low-work-function materials are desirable. On the other hand, because of the operative conditions that cathode materials may undergo inside the plasma chamber, also heat and corrosion-resistant materials are required. As a consequence, high-melting point materials are the major candidates. A good preliminary out gassing of the elements before the use is mandatory. Anyway the high operating temperature represent a

negative point for the use in ECRIS because it makes longer the switch-on procedure and even in presence of a load-lock system, a few hours are required for the replacement.

3.2 – *Work function and temperature*

As a first step it is worth to collect data on metal elements (the largest number of the elements are metals) and study them under the aspect of the work function E_w behaviour. In figure 12 the work function [26] parameter expressed in eV is reported versus the atomic number. It is easy to observe that the work function of a metal lies between 2 and 6 eV, with alkali metals having the lowest values for the work function, whereas a large amount of industrially relevant metals have a work function value around 4-5 eV. In spite of the low value of the work function, alkali elements are ineffective as cathode materials because they are soft and highly reactive materials.
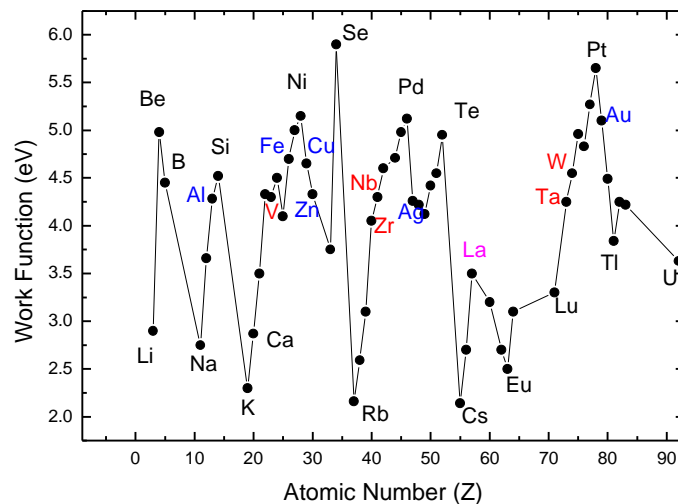
Figure 12. Work function (E_w) dependence on the atomic number (Z) for metal elements. Coloured symbols are used to label commonly used metals (in blue) and metals for special purpose (in red).

In order to fit all the features for a good cathode materials it would be useful to select the metals according to their melting point. Figure 13 reports the melting point dependence as a function of the atomic number of the element. We may observe as alkali metals have the lowest melting point, apart Hg which is liquid under normal conditions. Among metal elements, tungsten W with T_m=3407 °C has the highest melting point following only carbon whose melting point (3500 °C) is slightly higher. Besides tungsten several metals have a quite high melting point value. In particular Vanadium, Niobium, Molybdenum, Ruthenium,

Tantalum, Rhenium, Osmium and Iridium (elements labeled in red in Fig. 13) have melting point higher then 1900 °C. By comparing the two parameter we may conclude that elemental materials do not meet the low-work function, high melting point and high chemical stability requirements essential for a good cathode material. Nevertheless a high melting point determines the choice. For this reason, tungsten W with a work function of 4.5 eV is considered as the reference element material for such applications.

It seems that the possibility to use metal elements as electron donors is quite limited, because of the difficulty to run a hot metal cathode above 2000°C inside an ECRIS chamber without affecting negatively its performance. Irradiation and overheating of the chamber would certainly impair the positive yield of the cathode.
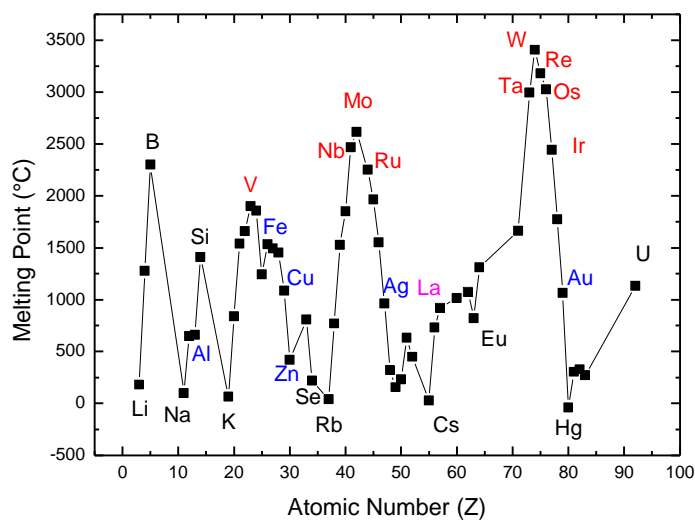

Figure 13. Melting point of metals as a function of their atomic number.

3.3 - Compound materials

An interesting solution may be represented by compound materials which are of use as electrons sources in facilities where electrons are used as a probe.

Transmission electron microscopes (TEM), scanning electron microscopes (SEM) and electron beam lithography (EBL) systems all require an electron source and hence a cathode material able to produce electrons. In these facilities electrons are produced and accelerated in order to form a bright and sharp electron-beam that, passing through a focusing lens system, impinges on a surface in order to analyse (TEM, SEM) or modify it (EBL). As a consequence an efficient electron source material in such system is essential and a study about the cathode materials which are used in this field is quite significant.

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Table 1 resumes the main characteristics of cathode materials used in electron scanning systems.

Material	Operating temperature (K)	Work Function (eV)	Current density (mA/sr)	Brightness (A/cm^{2}sr)	Life (hr)
W	2700	4.5	10^4	10^5	100
LaB$_6$	1800	2.7	10^5	10^6	5000
Zr-W	1900	3.1	10^3	10^9	5000

Table 1. Characteristics of cathode materials used in electron scanning systems [27].

3.4 - Lanthanum hexaboride LaB$_6$ as a good cathode material

The cathode material used in electron scanning systems is lanthanum hexaboride LaB$_6$ [27,28] used as a single crystal. In fact, LaB$_6$ matches all the characteristics of an optimum cathode material: it has a long life, a high stability and a high current capability compared to the conventional hairpin tungsten cathodes. Tungsten cathodes have several drawbacks such as: a high work function (4.5 eV), an insufficient beam current, and a short service life. LaB$_6$ has a lower work function (2.7 eV) than other materials, can easily emit electrons and their relative stability allows to use this material for a longer time (fig. 14).
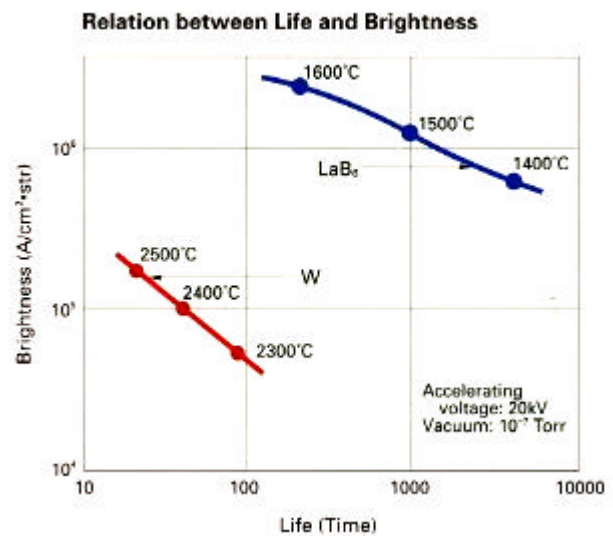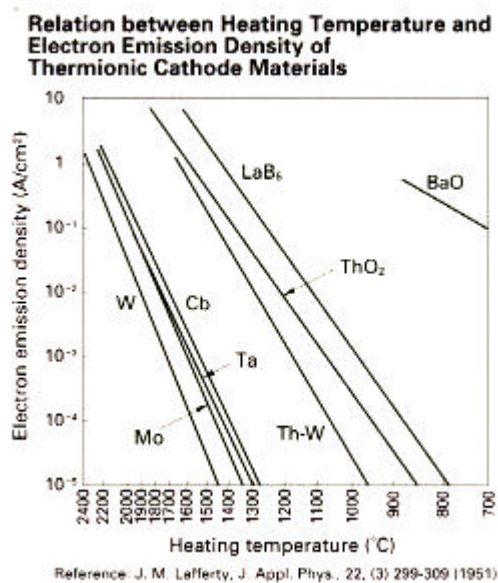
Figure 14. (Left) Current density as a function of heating temperature for several cathode materials. (Cb is the old symbol of Niobium Nb) (Right) Performance of LaB_6 compared to tungsten expressed in terms of brightness and lifetime.

For these reasons LaB_6 has been progressively employed as a material for cathodes instead of tungsten.

The main advantages of a LaB_6 can be resumed as :

- a high brightness: the LaB_6 – generated electron beam is ten times brighter than tungsten;
- a long life: heat and vacuum are the final issues that determines of any cathode tip's life, but at 1550 ºC and with a vacuum of 10^{-7} Torr, a service life of about 500 hours can be expected for LaB_6 cathodes;
- a high stability: LaB_6 cathode offers a stability better than 3% per hour at 1550 ºC.

Another possible improvement for the emitting properties of tungsten consists of coating its surface with a layer of zirconium oxide ZrO that allows to lower the work function barrier. Nevertheless, a significant drawback of W layered with ZrO is determined by the fact that this layer tends to evaporate and must be continuously replaced. As a whole W/ZrO cathodes do not have better performances then LaB_6 cathodes.

3.5 - LaB_6 deposition

Our intent is the insertion in a MDIS or ECRIS of an extraction electrode covered with a LaB_6 layer, having a well defined thickness and produced by chemical vapour deposition or sputtering deposition. The investigation on the optimal conditions of the sample preparation will be carried out, with a procedure schematically presented in fig.15. The deposition is done around the extraction hole, where the plasma density is higher in MDIS as well as in ECRIS.
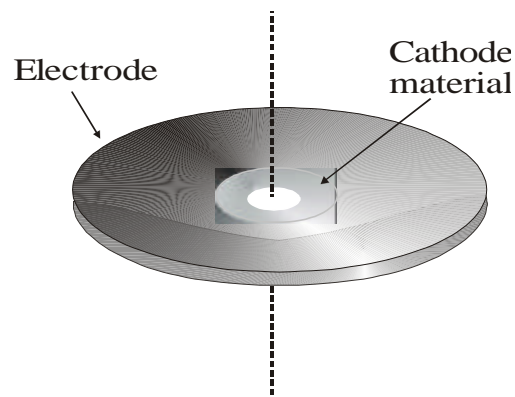

Figure 15. Cathode material deposited on an extraction electrode.

3.6 - Tantalum and Niobium as challenging materials for cathode materials

In Fig. 14 different cathode materials are compared under high temperature working conditions. Among the various materials shown in the figure at left, Ta and Nb can be considered as challenging materials for cathodes manufacturing. In particular, tantalum and niobium have a high corrosion resistance that makes these metals ideally suited for highly corrosive environments. Thus, tests with one of these materials can be done with a MDIS to verify such a possibility, regardless to the fact that it is not applicable to ECRIS. Finally, according to the experience of TU-Dresden, even Ir-made and W-made samples will be tested to check their lifetime when they are immersed in a low-temperature plasma as it is for MDIS, before testing it on ECRIS.

Figure 16. Allumina tube to be inserted in the TRIPS plasma chamber.

3.7 – Al$_2$O$_3$ insert

With respect to the wall coating and to the use of a thick Al chamber, a third way to the electron enrichment in MDIS and ECRIS plasma can be opened through the insertion of a thick Al$_2$O$_3$ tube inside the existing plasma chamber. A tube has been machined for the TRIPS (TRasco Intense Proton Source) source and it is shown in fig. 16.

Its dimension are the following: inner diameter 80 mm, outer diameter 90 mm (corresponding to the inner diameter of the TRIPS plasma chamber), length 95 mm.

If the results will be positive, a further test with a similar tube adapted to the dimension of the SERSE and CAESAR plasma chamber will be carried out.

4 - INFLUENCE OF A METAL-DIELECTRIC STRUCTURE USED AS ELECTRON DONOR ON THE PERFORMANCES OF ECR ION SOURCES

A new approach for the current increase of the high charge state ion beams delivered by electron cyclotron resonance (ECR) ion sources by using metal-dielectric (MD) structures characterized by high secondary electron emission properties was studied in the recent past at the Institut für Kernphysik (IKF) der J. W. Goethe Universität, Frankfurt/Main, Germany and Kernfysisch Versneller Instituut (KVI), Groningen, The Netherlands.

The intensities of argon ion beams extracted from the 14 GHz ECR ion sources were measured both in the standard mode of operation of the sources and in the presence of a MD structure. The results obtained when the MD structure is used show a net shift of the beam intensity towards higher charge states as compared with the usual standard plasma chamber of the ECR ion sources. With the MD structure the yield of highly charged ions of the ECRIS are significantly enhanced [29]. Ion current enhancement factors of up to two orders of magnitude were obtained for Ar^{16+}.

4.1 - Experimental procedure

The MD ($Al-Al_2O_3$) cylinder was produced out of a 1 mm thick sheet of pure aluminium rolled in the form of a tube. The emissive dielectric Al_2O_3 layer was obtained by a special electrochemical technology. The MD cylinder was similarly installed in the stainless steel plasma chambers, symmetrically with respect to the hexapole magnet for plasma radial confinement. The source geometries and the main electrical parameters were kept unchanged during all measurements. The extraction voltage was between 10 and 25 kV and

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measurements were performed at RF power levels of 200 to 800 W. Two types of gas were used to feed the sources: pure argon and mixing gas (Ar+O$_2$). In all experiments, the beam optical elements were optimized for the transport of Ar^{12+} ions.

4.2 - Results

The effect of the MD cylinder introduced in the plasma chamber of the IKF ECR ion source is illustrated in the figures 17-20.

In figure 17 the charge state distributions of argon ion beams for charge states q > 8 are presented, for three different materials used for the plasma chamber inner surface (stainless steel, Al, MD), at RF power = 800 W for the case of pure argon as working gas. The outer surface of the cylinder remained metallic in order to provide a good electric and thermal contact with the plasma chamber wall.

The CSD clearly demonstrate that, the output of the source equipped with the MD cylinder is much higher than that of both the standard source and the source equipped with a cylinder of technical aluminium. For charge states q > 10, the source output was higher by almost two orders of magnitude when the MD cylinder is used. It is also evident that the MD structure effect increases with increasing charge state. The effect of the aluminium cylinder is much lower. Enhancements of the source output of only 30-50% have been observed in this case for charge states q > 8, which are the most interesting for us.

In figure 18 the same plots are given as in figure 17 but for a mixture of Ar+O$_2$ as source feed gas (mixing gas method). In this case the increase is not so large but it is still remarkable.

Fig. 17. CSD's of argon ions for the stainless steel plasma chamber (open circles), aluminium cylinder (open triangles) and MD cylinder (solid squares) for microwave RF power of 800 W
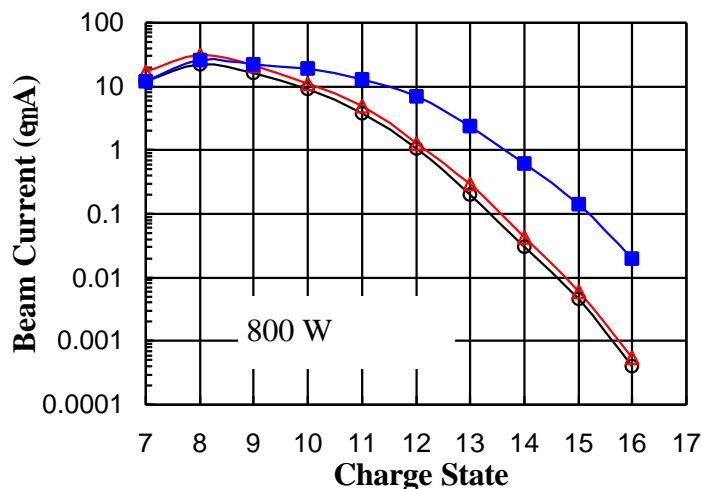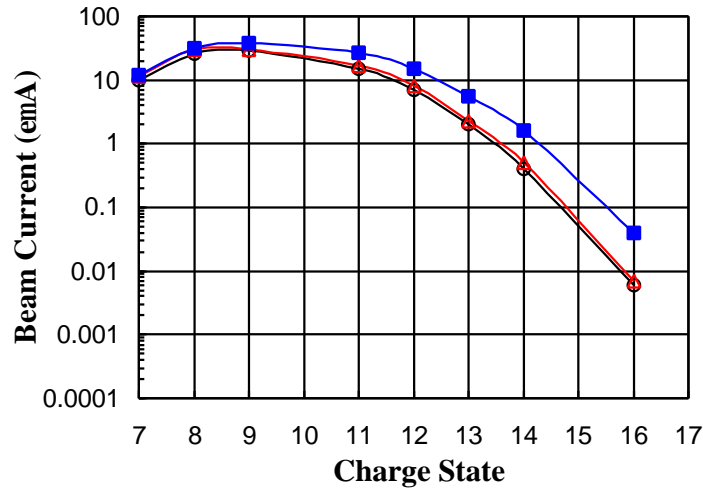
Fig. 18. CSD's of argon ions for the stainless steel plasma chamber (open circles), aluminum cylinder (open triangles) and MD cylinder (solid squares) for microwave power P_{RF} 800 W. Source gas: mixing gas (Ar+O_2).

The enhancement factors of the argon ion beam currents for charge states q = 2 ÷ 16 due to the MD cylinder are given in figure 19 for both pure argon and mixing gas, at P_{RF} = 800 W.
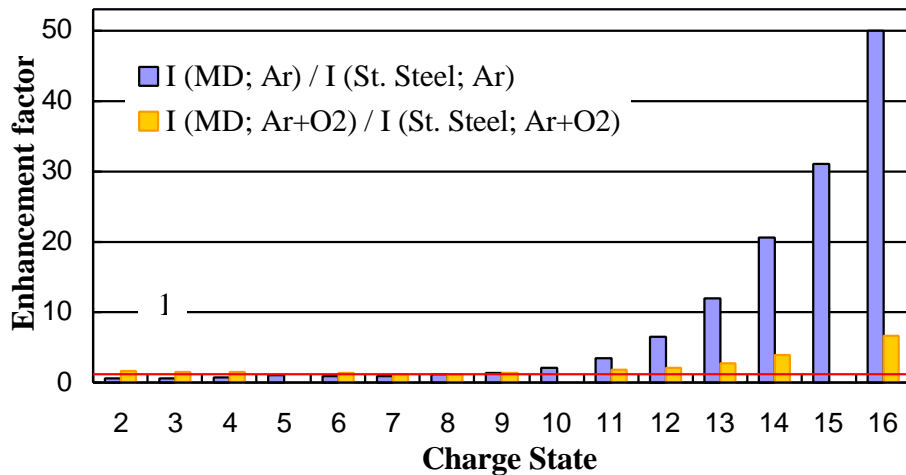
Fig. 19. Enhancement factor of the argon ion current due to the MD cylinder at P_{RF} = 800 W

The relative effect of the MD cylinder and of the mixing gas method on the source output is well illustrated in figure 20 where the CSD at P_{RF} = 800 W are given for the standard source and the source with MD cylinder both for pure argon and mixing gas.

It can be seen that for q > 11 the output of the source with MD cylinder and pure argon is higher than that of the source with stainless steel or aluminum walls and with mixing gas.

It should be noted that even by carefully degassing the ion source after insertion of the MD structure, still a more or less constant contribution of oxygen was observed in the charge state spectra. This contribution depends on the method of production of the cylinder but was much smaller (1-10%) with respect to the relative pressures necessary for gas mixing. As a consequence a supplementary advantage of the MD structures results from the fact that the use of Ar^{5+}, Ar^{10+} and Ar^{15+} beams is not excluded like in the case of the mixing gas contamination. In order to obtain the maximum currents, the combination of both MD structures and gas mixing methods can yield a further increase (about a factor two).

The very interesting results obtained with the IKF ECR ion source, were partially confirmed on a different 14 GHz ECR ion source, of CAPRICE type, used as injector in the AGOR cyclotron at the KVI, Groningen.

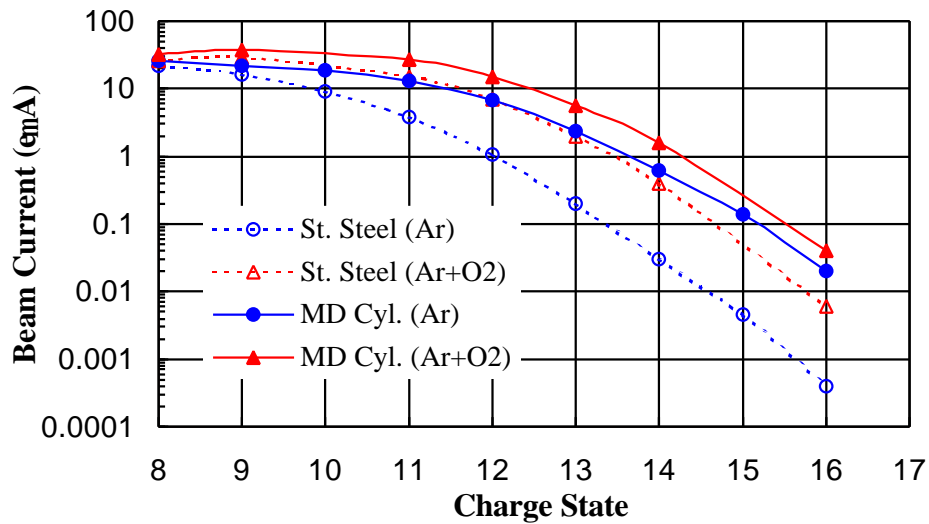**Fig. 20**. Effect of the MD cylinder and mixing gas method on the ECRIS argon ion beam output.

A synthesis of the most relevant measurements at the KVI ECR ion source is given in table 2. For this source the electron deficit is not so large and the effectiveness was less pronounced. It was anyway obtained a level of Ar^{16+} ion current and Ar^{17+} ion current much larger than before, even in presence of a smaller rf power.

Spectrum	Method MD	Method Gas Mixing	RF Power (W)	CSD Peak	Ar^{12+} (eµA)	Ar^{14+} (eµA)	Ar^{16+} (eµA)	Ar^{17+} (eµA)	O^{3+} (eµA)	O^{5+} (eµA)
A	No	no	320	9	1.8	0.1	0.001	-	0.040	0.010
B	no	yes	730	11	17.5	3.7	0.17	-	17.4	12.2
C	yes	no	310	11	10.5	3.5	0.30	0.010	1.9	0.6
D	no	yes (reduced)	320	9	10.3	1.9	0.06	0.003	2.5	0.6
MD best (opt. 16+)	yes	no	250	11	8.2	3.3	0.36	0.015	1.1	0.3

Table 2. Synthesis of the measurements carried out at the KVI ECRIS (all spectra optimized for Ar^{12+} except MD best)

4.4 - Comments

The experiments carried out on the IKF and KVI ECR ion sources, clearly demonstrate the very good capability of the MD structures to enhance the output of the highest charge states of an ECRIS. The similar results of the experiments with a MD cylindrical liner introduced in the IKF and KVI ECR ion sources lead to the following conclusions:

1. The presence of the MD liner in the plasma chamber determines a remarkably stable operation of the source, and therefore likely a magneto-hydrodynamic stability of the ECR plasma (lower plasma potential can be responsible of such phenomenon).

2. The high charge state (q>10) ion output of the source operated with pure argon when using the MD liner is much higher than the typical values obtained from the ion sources in the same mode of operation and comparable or even higher for the very high charge states (q>14) than those obtained in the mixing gas mode of operation.

3. The presence of the MD liner allows working at much lower RF power (300 W instead of 700 W in the case of mixing gas) for comparable or even better results.

4. Due to the excellent stability of the source and of the lack of important contaminants in the presence of the MD liner, it was possible to make precise measurements to determine unambiguously the Ar^{17+} peak at the KVI ECRIS.

5. The high charge state beam increase when using the MD liner is clearly not due to a gas mixing effect given by the oxygen sputtered from the oxide layer.

6. The necessity for a more deep knowledge of the physical processes in the ECR plasma related to the MD structure performances was put in evidence and new experiments are to be realized. In this sense a proposal to reproduce the same experimental procedure with the SERSE source at INFN-LNS was recently accepted and the beamtime was allocated in July 2003. The experiment will be quite simple and will consist of the comparison of the source performance without the MD liner (Oxygen and Argon, pure gas and mixed gas) and with the MD liner (Oxygen and Argon, pure gas and mixed gas). The combined effect of biased disk and MD liner will be also studied.

5 - Conclusions

Many solutions have been set up to increase the plasma density in ECRIS and MDIS, but there is no evidence that the best solution has been yet found. On the other way, the progress of materials science offers continuously new possibilities. Some of these materials and techniques are going to be exploited at different European laboratories, in a joint effort to get a clear picture of the involved phenomena and to optimise the performance by means of an appropriate handling of these techniques. Table 3 summarizes all the tests which are proposed in the present paper to be carried out with the different ion sources at LNS in the frame of the EDIPO project, funded by the Fifth National Committee of INFN.

Experiment	TRIPS	CAESAR	SERSE
Biased disk position optimization		X	X
Biased disk material choice		X	X
Biased disk dimension and shape		X	X
Al_2O_3 coated electrode	X		X
Al_2O_3 tube	X		
La_2B_6 insertion	X		
Ta, Nb cathodes	X		
Ir, W cathodes and other materials	X	X	
MD liner			x

Table 3 A list of the experiments to be carried out at LNS in order to determine the role of electron donors.

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