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Ionization efficiency studies for xenon ions with the superconducting ECR ion source VENUS

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Abstract

Ionization efficiency studies for high charge state xenon ions using a calibrated gas leak are presented. A 75% enriched ^{129}Xe gas leak with a gas flow equivalent to 5.11pµA was used in all the measurements. The experiments were performed at the VENUS (Versatile ECR ion source for Nuclear Science) ion source for 18 GHz, 28 GHz and double frequency operation. Overall, total ionization efficiencies close to 100% and ionization efficiencies into a single charge state up to 22% were measured. The influence of the biased disk on the ionization efficiency was studied and the results were somewhat surprising. When the biased disk was removed from the plasma chamber, the ionization efficiency was dramatically reduced for single frequency operation. However, using double frequency heating the ionization efficiencies achieved without the biased disk almost matched the ionization efficiencies achieved with the biased probe. In addition, we have studied the influence of the support gas on the charge state distribution of the xenon ions. Either pure oxygen or a mixture of oxygen and helium were used as support gases. The addition of a small amount of helium can increase the ionization efficiency into a single charge state by narrowing the charge state distribution. Furthermore by varying the helium flow the most efficient charge state can be shifted over a wide range without compromising the ionization efficiency. This is not possible using only oxygen as support gas. Results from these studies are presented and discussed.

1. Introduction

For radioactive ion beam post accelerator facilities, using a charge breeder coupled to an accelerator is a cost effective alternative compared to accelerating singly charged ions with subsequence stripping to higher charge states. Charge breeding becomes especially favorable above a nuclear mass of 100 [1]. Therefore, charge breeding systems are in use at REX ISOLDE [2] and are under development for ISACII in TRIUMF [3], for the CARIBU project in Argonne National Laboratory [4], and planned for the coupled cyclotron project at Texas A&M [5].

Presently, there are two complementary technologies used as charge breeders: EBIS/EBIT sources [2] (operated stand alone or in conjunction with a Penning trap) or ECR ion sources [6,7]. Both systems have distinct advantages and disadvantages. The main advantage of an ECR ion source is the much higher ion storage capacity and its CW operation. A high performance ECR ion source with a modest plasma volume can easily accept 10^{13} radioactive ions per seconds. Contrary, the storage capacity of an EBIS or EBIT source is limited by the maximum charge density of its electron beam and the trap lengths. EBIS/EBIT can typically store several orders of magnitude less ions[2] than an ECR ion source. Furthermore, an EBIS has to be operated in pulsed mode. On the other hand EBIS/EBIT might offer advantages over ECR ion sources in terms of breeding time, beam impurities and efficiency. Therefore, it would be advantageous for a next generation radioactive ion beam facility to have both techniques available to optimize the radioactive ion beam production case by case.

In this paper, we report on a study of 0^+ to n^+ ionization rather than commonly reported 1^+ to n^+ ionization. The goal is a better understanding of which parameters influence the ionization efficiency in ECR sources. The VENUS ECR ion source used in this study is a fully superconducting ECR ion source developed at the Lawrence Berkeley National Laboratory. It was designed for optimum operation at 28 GHz with an axial field of up to 4T at the injection, up to 3T at the extraction and a radial field of 2T at the plasma chamber wall. Its design and performance are described in detail in [8,9] and several references within these papers. VENUS, like most modern ECR sources, has a biased disk located on axis at the microwave injection side of the plasma chamber. Usually, the disk is biased negatively with respect to the plasma chamber wall and serves as an electron donor for the plasma. This reduces the plasma potential and enables the ECR plasma to operate stably at lower neutral pressure, which enhances the production of high charge state ions. Unfortunately, the biased disk must be removed to convert an ECR source into a charge breeder, so that the singly charged ions can be axially injected. Therefore, we studied the effect of removing the biased disk on the ionization efficiency. Measurements were performed on the VENUS ECR ion source at 18 and 28 GHz with the biased disk installed, with the biased disk electrically connected to the plasma chamber and the disk completely removed from the system.

For all measurements presented in this paper, a calibrated gas leak containing 75% enriched ^{129}Xe has been used. It has a nominal leak rate of $5.3\cdot10^{-11}$moles/sec, which is equivalent to a current of 5.11 pμA or a particle flow of $3.2\cdot10^{13}$ particles/sec (75% of that value is ^{129}Xe). The quoted uncertainty for this calibrated leak is ±9.2%. In addition, there is some uncertainty about the isotopic enrichment since the other Xe isotopes cannot be resolved in the spectrum. However, since all the measurements were done with the same calibrated leak and set-up, the relative efficiencies achieved for each experiment can be compared. The total ionization efficiency was determined by summing up over all particle currents in each charge state and comparing this sum to the neutral particle flow into the plasma. Likewise the ionization efficiency into a single charge state was determined by comparing the particle current of a particular charge state to the neutral particle flow into the plasma.

The VENUS ion beam transport and analysing system[10] is designed to transport intense ion beams with high transmission. An ion beam transmission of 80% or higher was achieved for the experiments described.

2. Ionization efficiency measurements with an optimized biased disk and with a biased disk electrically connected to the plasma chamber

A series of ionization efficiency measurements were performed using ECR heating at either 18, 28 GHz or both frequencies (‘double frequency heating’) simultaneously. For each experiment the biased disk voltage has been optimized for maximum ion beam current. Ionization efficiencies up to 22% into a single charge state and total ionization efficiency of almost 100% were measured. Using pure oxygen as support gas the charge state with the highest ionization efficiencies were Xe^{26+} for 18 GHz operation, and Xe^{27+} and Xe^{28+} for 28 GHz operation. As an example, figure 1 shows an optimized ionization efficiency using 1000W of 18 GHz plasma heating ($^{129}\mathrm{Xe}^{24+}$ can not be resolved from the O^{3+} peak and is therefore not shown in the graph). Figure 2 shows the influence of the coupled microwave power on the charge state distribution for a double frequency heated source using mainly 28 GHz. A field profile with a minimum field value of .43T, which is 43% of the resonance field for 28 GHz and 67% for 18 GHz, was used for these measurements. The peak in the maximum ionization efficiency shifts to higher charge states with higher total microwave power, but the charge state distribution broadens in turn reducing the efficiency into a single charge state.

Connecting the biased disk electrically to the plasma chamber as opposed to optimizing the biased disk voltage had surprisingly little effect on the ionization efficiency in single or double frequency mode. In both cases the overall ionization efficiency is nearly the same and close to 100% for similar power settings and support gas flows. The charge state distribution shifts slightly to lower charge states when the biased disk is electrically connected to the chamber. As an example the ionization efficiency for 4kW 28 GHz and 500W 18 GHz microwave power is shown in figure 3a. A similar (small) shift was observed in the mixing gas spectrum. Figure 3b shows the particle currents in pμA versus the oxygen charge state.

3. Ionization efficiency measurement with the biased disk removed

For these measurements the biased disk was removed leaving a hole on axis to better simulate the actual set up of a 1^+ to n^+ charge breeder system. After the biased disk had been removed the total current extracted from the source generally dropped by a factor of 3 to 4 and the charge state distribution of the support gas was dramatically effected (see section 3.2).

3.1. 18 GHz Operation

For 18 GHz operation, the ionization efficiency for single frequency operation was dramatically reduced. At best an efficiency of 10% into a single charge state could be achieved compared to an ionization efficiency of 22% into a single charge state with the biased disk installed and its voltage optimized. Figure 4 shows a comparison of the highest efficiencies achieved with 18 GHz when the biased disk is installed with its voltage optimized compared to efficiencies when the biased disk is removed. Identical magnetic confinement field configurations were used, and in both cases 1000W of 18 GHz were injected into the VENUS source. The main difference between the two tunes is the neutral gas pressure required to maintain a stable plasma discharge. With the biased disk installed the best ionization efficiency was achieved in the pressure range of 1.5 to $1.8 \cdot 10^{-7}$ mbar measured at the plasma chamber entrance. With the biased disk removed, much higher mixing gas flows had to be used to sustain stable operation. It was not possible to establish a stable discharge below a pressure of $2.6 \cdot 10^{-7}$mbar. At this high operating pressure the total ionization efficiency is reduced and furthermore, the charge state distribution broadens, which further decreases the ionization efficiency into a single charge state. This result is consistent with the general understanding of the function of the biased disk as an electron donor, which increases the plasma confinement time and allows sustaining plasma at lower neutral gas pressures.

3.2. 28 GHz and double frequency operation

A similar result was found using 28 GHz heating, but the performance drop in efficiency could be compensated to some extent since more power was attainable to heat the discharge. To peak on Xe^{26+} almost 3kW 28 GHz power are needed while only about 1kW is needed with the biased disk installed and optimized. The ionization efficiency for Xe^{26+} is reduced from 20% to 13% in this case (Figure 5). Similar to the 18 GHz heated source, the gas pressure had to be higher to sustain a stable discharge. More microwave heating power could compensate somewhat for the higher neutral gas pressure, but overall lower ionization efficiencies are achieved.

But surprisingly when a few hundred watts of 18 GHz were added, the ionization efficiency could be restored to levels very close to efficiencies achieved with the biased disk in place and optimized although higher heating power was required. This is illustrated in Figure 6. The ionization efficiency achieved using single frequency alone (round symbols) and the efficiency achieved using double frequency (square symbols) are plotted. Both ionization efficiency distributions were produced using the same field configuration and leaving all other tuning parameters unchanged. In both cases about 2900W microwave power were used, but in the double frequency heated case 300W of 18 GHz microwave power was added to 2600W 28 GHz. As in the earlier measurements, a field profile with a minimum field value of .43T, which is 43% of the resonance field for 28 GHz and 67% for 18 GHz, was used for these measurements. As can be seen in Figure 6, the double frequency case is clearly more efficient than the single frequency case, which suggests that higher plasma densities can be achieved using double frequency heating. Using double frequency the optimal gas pressure for the discharge was similar to the pressures used with the biased disk installed around 1.3 to $1.7 \cdot 10^{-7}$mbar.

However, the support gas charge state distribution remains suppressed and does not improve when the source is double frequency heated. The total extracted current is reduced in both cases by a factor of 3 to 4 without the biased disk installed. As shown in Figure 7, the distribution (b) for the single frequency heating configuration with 28 GHz and (c) for the double frequency heating with 28 GHz and a few hundred watts of 18 GHz are nearly identical. As comparison, the oxygen charge state distribution from a comparable ionization efficiency measurement, but with an optimized biased disk is shown in graph 7a, for which the oxygen charge state distribution peaks on O^{6+}.

3.3. Influence of the mixing gas on the charge state distribution

The influence of the support (mixing) gas was studied in more detail for the double frequency heating case with the biased disk removed. The choice and amount of support gas used is an important tuning parameter in terms of ion source efficiency. In the VENUS ECR ion source, in most cases oxygen is used as mixing gas for two reasons: First, it is a light gas, which substantially enhances the production of high charge state heavy ions due to the gas mixing effect [11]. Secondly, for aluminum plasma chambers (as incorporated in the VENUS source) oxygen is an especially favorable mixing gas. It conditions the plasma chamber wall to form a thin layer of aluminum oxide, which has a high secondary electron coefficient, which helps to replenish low energy electrons in the plasma similar to the biased disk.

An optimum gas flow can be determined for pure oxygen as support gas in terms of efficiency into a single charge state and total efficiency gas. Adding more gas to the plasma will shift the charge state distribution to the lower charge states, but decreases the total ionization efficiency. This is shown in Fig 8, the total ionization efficiency decreases from nearly 90% to less than 60%.

Next helium was added as additional mixing gas. For all the data presented the direct pressure reading from the cold cathode ionization gauge is quoted. However it should be noted that for helium the correction factor for the pressure reading is about a factor of 5 to 5.9. Therefore, the neutral gas pressures for the added helium are about a factor of 5 to 5.9 higher than indicated in the text.

By adding a small amount of helium as additional mixing gas to the source plasma, it is possible to increase the ionization efficiency into a single charge state, since the charge state distribution narrows. This is shown in Figure 9, where the injection pressure of the source was increased from $1.7\cdot10^{-7}$ to $1.85\cdot10^{-7}$mbar by adding helium to the plasma. The CSD was shifted slightly to lower charges states, but the ionization efficiency into a single charge state was increased from 18% to 22%.

When more helium support gas is added to the plasma it is possible to shift the charge state distribution without loosing too much efficiency into a single charge state. Figure 10 shows how the peak of the most efficient charge state is shifted towards lower charge states as more helium is added. However, if too much gas is added the source the total ionization efficiency decreases and the charge state distributions widens reducing as well the ionization efficiency into a single charge state (see figure 10, triangular symbols).

To illustrate the wide shift in the ion charge state distribution, Figure 11 shows two ion spectra, in which either pure oxygen (solid line) or oxygen and helium (dashed line) are used as support gases. In addition, the helium mixing gas improves the charge state distribution of the oxygen support gas to peak on O^{6+} compared to O^{2+} for the pure oxygen operation.

4. Discussion

Tuning parameters in ECR ion sources are highly coupled and it is always difficult to draw clear conclusions. But the experimental results from these efficiency measurements indicate that techniques that improve the ion source stability, confinement and plasma density also improve the ionization efficiency. Even while it is surprising how well double frequency heating can compensate the absence of the biased disk from the plasma chamber, the results are consistent with a general trend in ECR ion sources that double frequency heating improves stability and plasma confinement. However, double frequency does not improve the oxygen mixing gas spectrum as might be expected. Adding helium to the plasma has two effects on the plasma. It shifts the charge state distribution for the light gas (oxygen) to higher charge states as it would be expected from the mixing gas effect, but shifts the heavier ions to lower charge state. Since the overall ionization efficiency is not decreased by adding the helium gas to the source, it indicates that the neutral pressure in the plasma remains low and that the degree of ionization in the plasma stays high. This is in contrast to the dependences measured for increased oxygen flow. At constant power, the overall ionization efficiency decreases when the neutral pressure in the plasma increases by adding more oxygen.

5. Acknowledgments

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6. References

1 P.N. Ostroumov, K.W. Shepard, A.A. Kolomiets et al., Proceedings of the Particle Accelerator Conference 2001, Chicago, 2001

2 F. Wenander, P. Delahaye, R. Scrivens et al., RSI **77** (03B104), 03B104-101-104 (2006).

3 R. Baartman R.E. Laxdal, P. Bricault, M. Dombsky, G. Dutto, K. Fong, A. Mitra, and P. Schmor R. Poirier, G. Stanford, A. Facco, Proceedings of the 20th LINAC Conference, Monterey, California, 2000

4 R. Vondrasek, R. C. Pardo, T. Kulevoy et al., Proceedings of the 17th intern. Workshop on ECR Ion Sources, Lanzhou, China, High Energy Physics and Nuclear Physics, China, 2006

5 D. May, Texas A&M Upgrade, 2004.

6 R. Geller, C. Tamburella, and J.L. Belmont, RSI **67** (3), 1281-1285 (1996).

7 T. Lamy, R. Geller, P. Sortais et al., RSI, submitted (2005).

8 D. Leitner, C. M. Lyneis, T. Loew et al., RSI **77** (03A302) (2006).

9 D. Leitner, D.S. Todd, M.L. Galloway et al., Journal of HEP&NP, Chinese Physical Society (2006).

10 M.A. Leitner, C.M. Lyneis, D.C. Wutte et al., Physica Scripta **T92**, 171-173 (2001).

11 A.G. Drentje, A. Girard, D. Hitz et al., RSI **71** (2), 623 (2000).

Figure Captures

Figure1 The efficiency was optimized onto Xe^{26+} injecting 1 kW 18 GHz microwave power into the plasma. The single charge state efficiencies are plotted for the xenon charge state distribution.

Figure 2 shows the influence of the coupled power on charge state distribution and the most efficient charge state. As more power is coupled the most efficient charge state is shifting to higher charge states. The 28 GHz power is listed first in the legend followed by the 18 GHz power.

Figure 3 3a) shows the ionization efficiency for the xenon charge state distribution and 3b) shows the particle distribution into the charge states of the oxygen mixing gas.

Figure 4 Ionization efficiencies for single frequency heating with the biased disk potential optimized to -33V and the biased disk removed from the ECR ion source, 18 GHz field (optimized) and 1 kW of 18 GHz microwave

Figure 5 Single frequency heated ionization efficiency when the biased disk is installed and optimized, and when the biased disk is removed. To achieve a similar charge state distribution almost three times the power is required.

Figure 6 Ionization efficiencies for double and single frequency heating when the biased disk was removed from the ECR. Using double frequency heating, the ionization efficiency into a single charge state can be optimized and is similar to the values achieved when the biased disk is installed and the potential optimized.

Figure 7 Charge state distribution of the oxygen mixing gas with biased disk installed and optimized (a), with the biased disk removed for single (b) and double frequency operation (c).

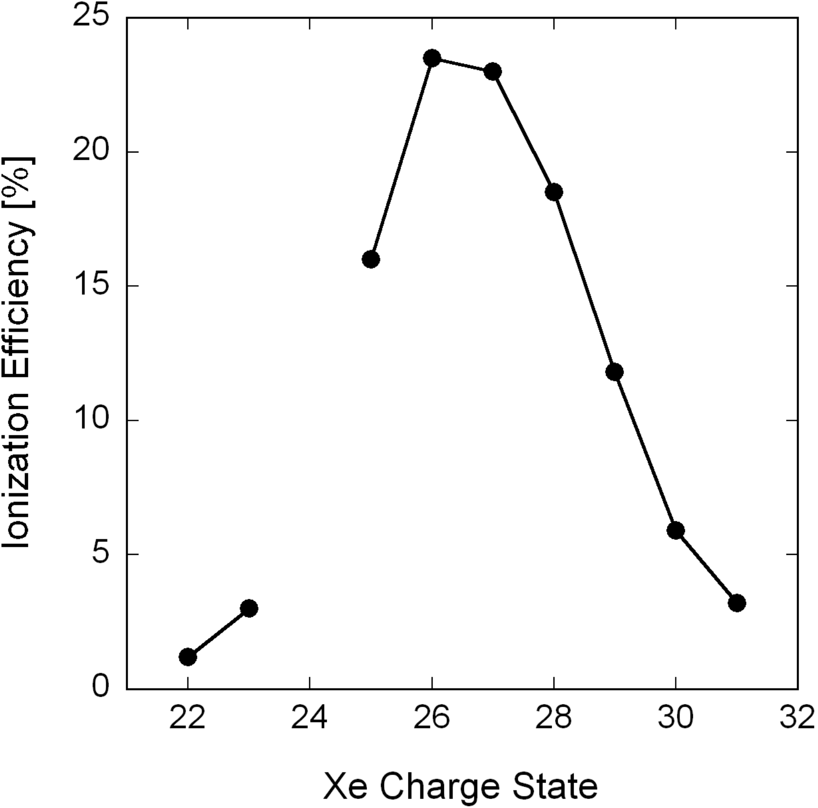
Figure 8 The ionization efficiency into a single charge state is plotted in dependence of the oxygen mixing gas flow, when all other source parameters are unchanged.

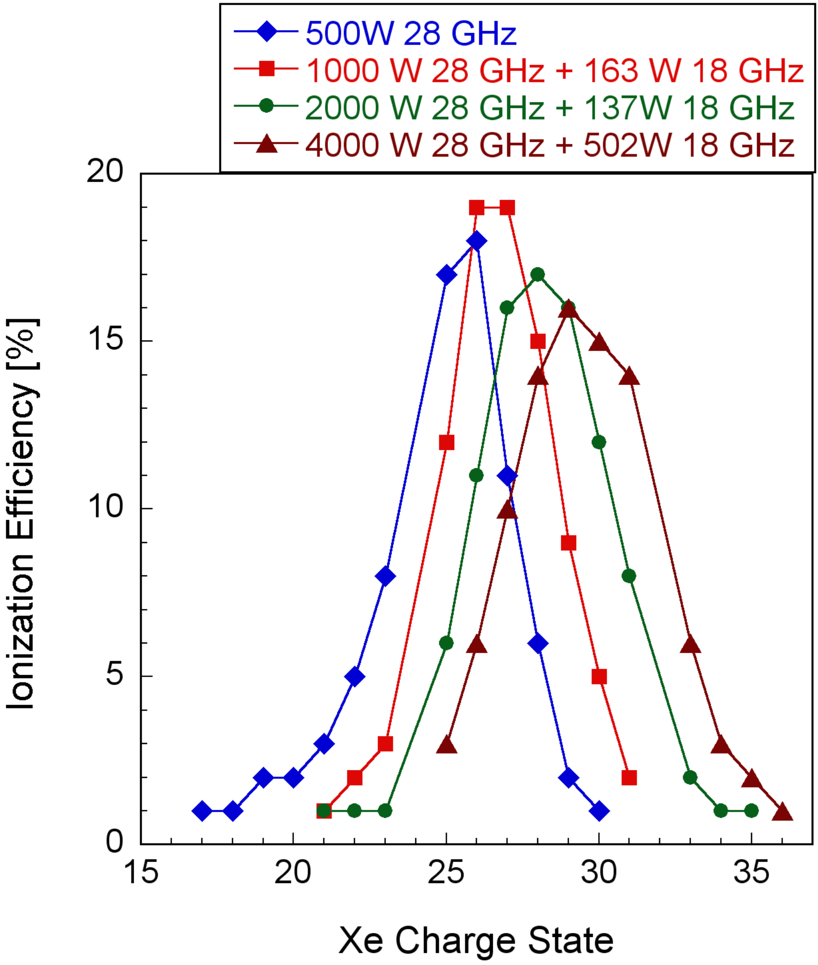
Figure 9

Adding a small amount of He shifts charge state distribution and efficiency to lower charge states The square symbols represent the efficiency achieved with pure oxygen gas, the round symbols are used for an efficiency measurement in which a small amount of helium was added to the plasma with the oxygen support gas flow unchanged.

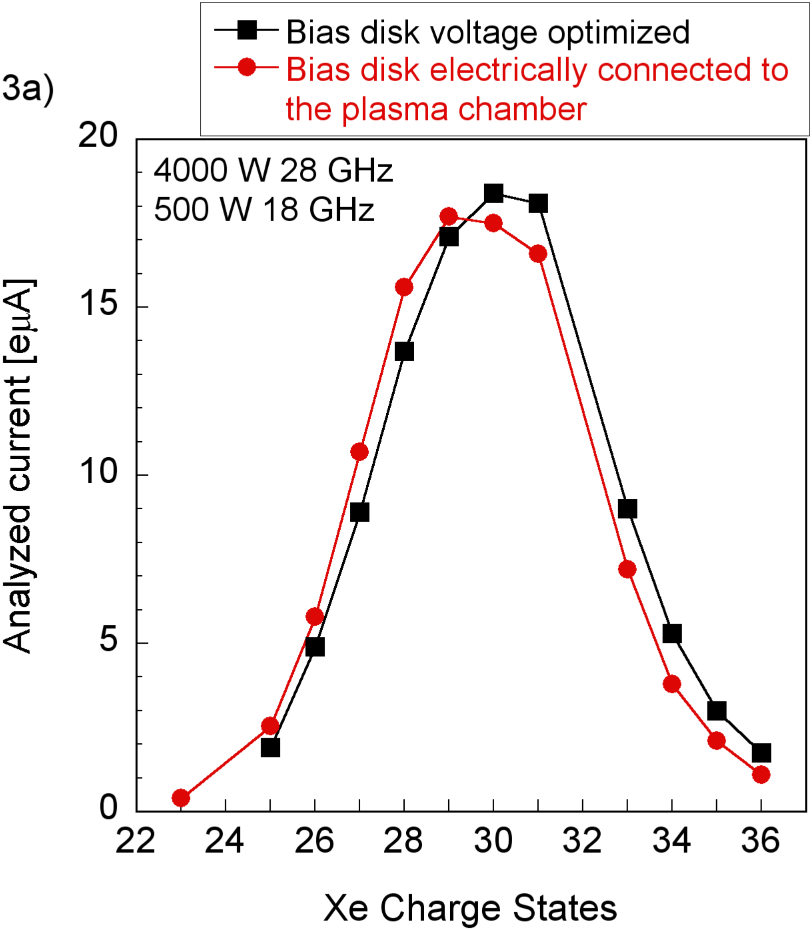
Figure 10 Adding more helium to the source as support gas shifts the charge state distribution to lower charge states.

Figure 11 Charge state distribution for efficiency measurements using oxygen as mixing gas (solid line) and using oxygen and helium as mixing gas (dashed line). The addition of helium moves the xenon to higher M/Q or lower charge state.

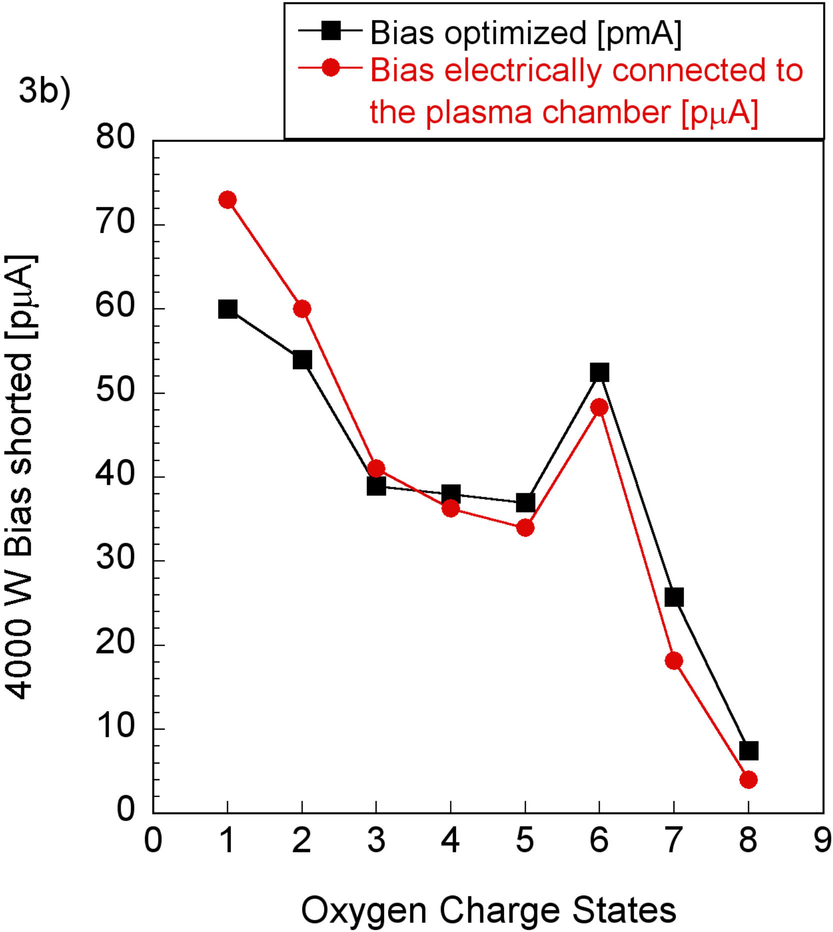

Ionization Efficiency [%]
0
5
10
15
20
25
22
24
26
28
30
32
Xe Charge State

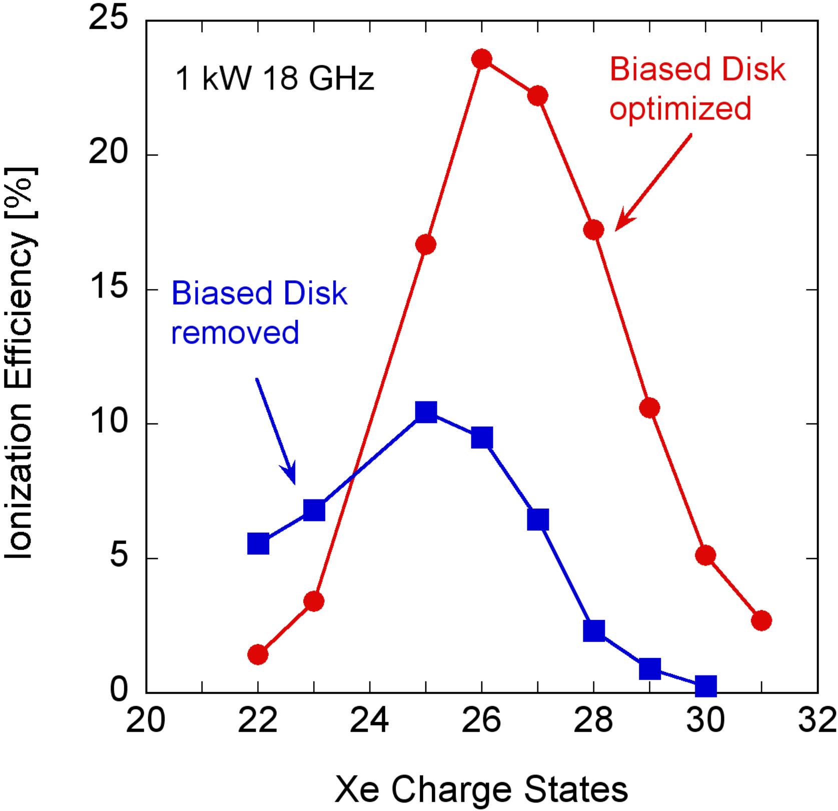

500W 28 GHz
1000 W 28 GHz + 163 W 18 GHz
2000 W 28 GHz + 137W 18 GHz
4000 W 28 GHz + 502W 18 GHz
Ionization Efficiency [%]
0
5
10
15
20
15
20
25
30
35
Xe Charge State

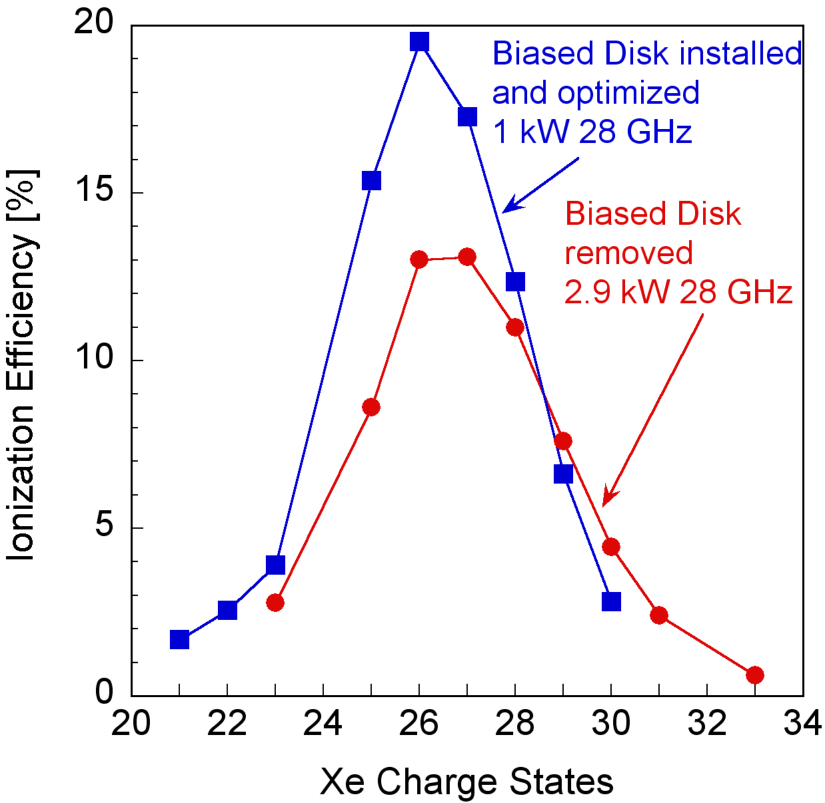
3a)


Bias disk voltage optimized
Bias disk electrically connected to the plasma chamber
4000 W 28 GHz
500 W 18 GHz
Analyzed current [eμA]
0
5
10
15
20
22
24
26
28
30
32
34
36
Xe Charge States

3b)


Bias optimized [pmA]
Bias electrically connected to the plasma chamber [pμA]
4000 W Bias shorted [pμA]
0
10
20
30
40
50
60
70
80
0
1
2
3
4
5
6
7
8
9
Oxygen Charge States


1 kW 18 GHz
Biased Disk optimized
Biased Disk removed
Ionization Efficiency [%]
Xe Charge States
0
5
10
15
20
25
20
22
24
26
28
30
32


Biased Disk installed
and optimized
1 kW 28 GHz
Biased Disk
removed
2.9 kW 28 GHz
Ionization Efficiency [%]
Xe Charge States
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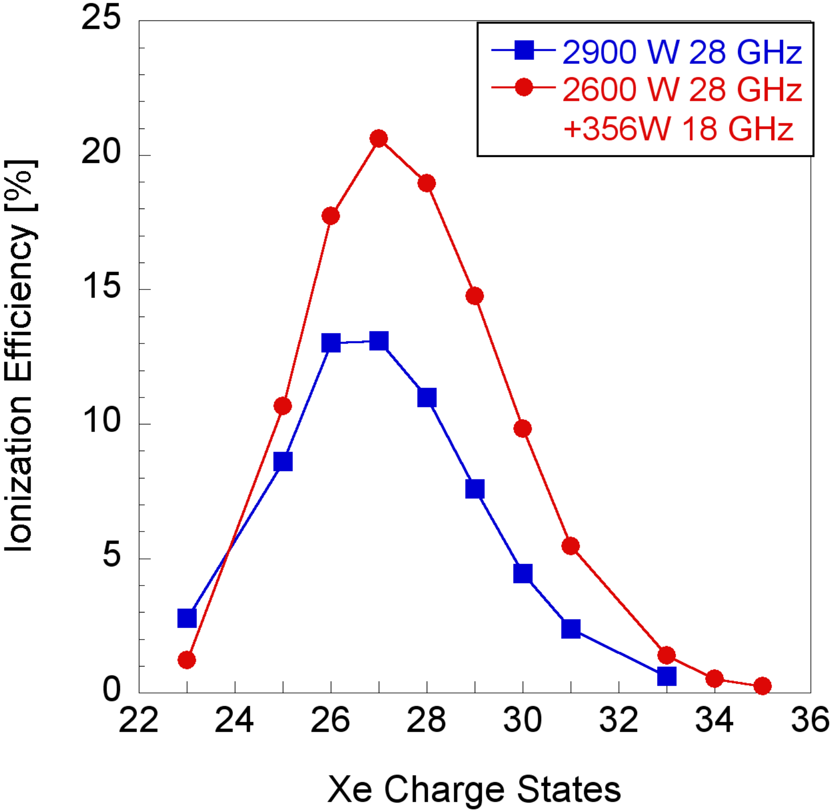
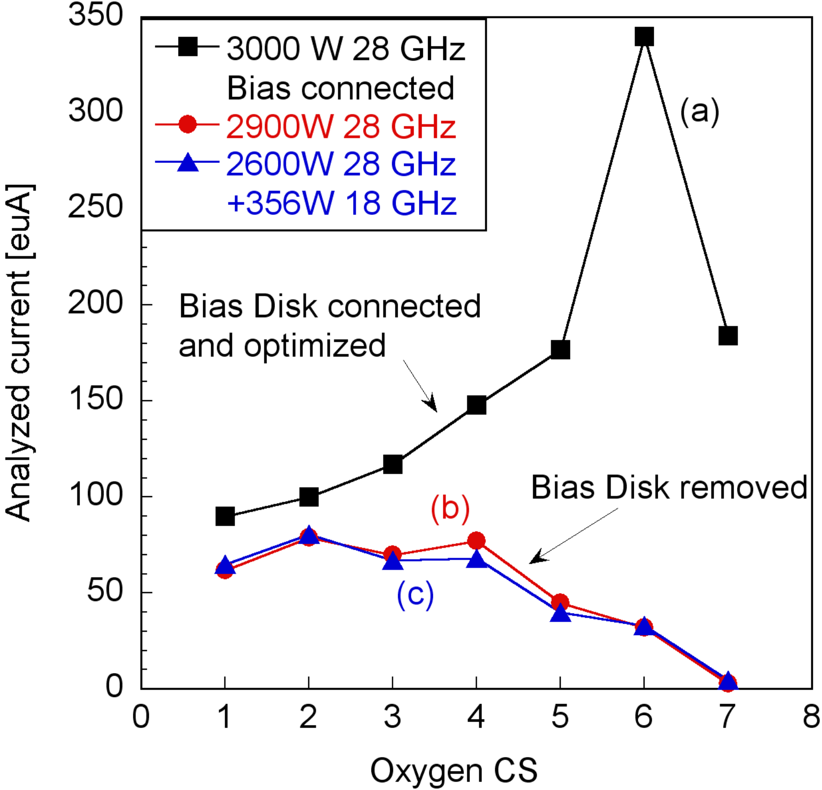
5
10
15
20
20
22
24
26
28
30
32
34


2900 W 28 GHz
2600 W 28 GHz
+356W 18 GHz
Ionization Efficiency [%]
Xe Charge States
0
5
10
15
20
25
22
24
26
28
30
32
34
36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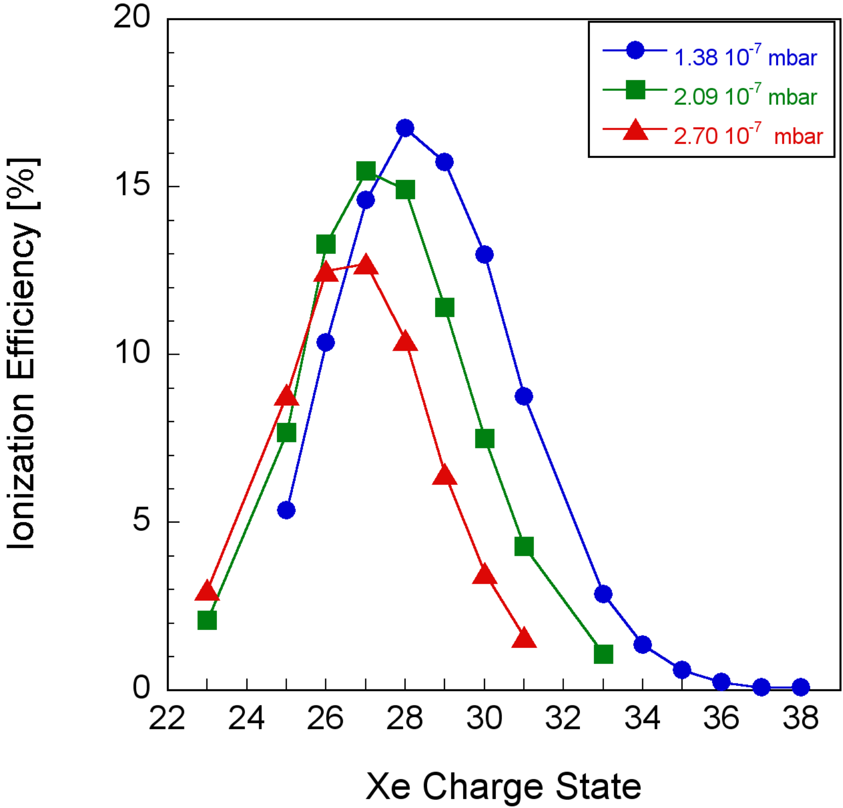
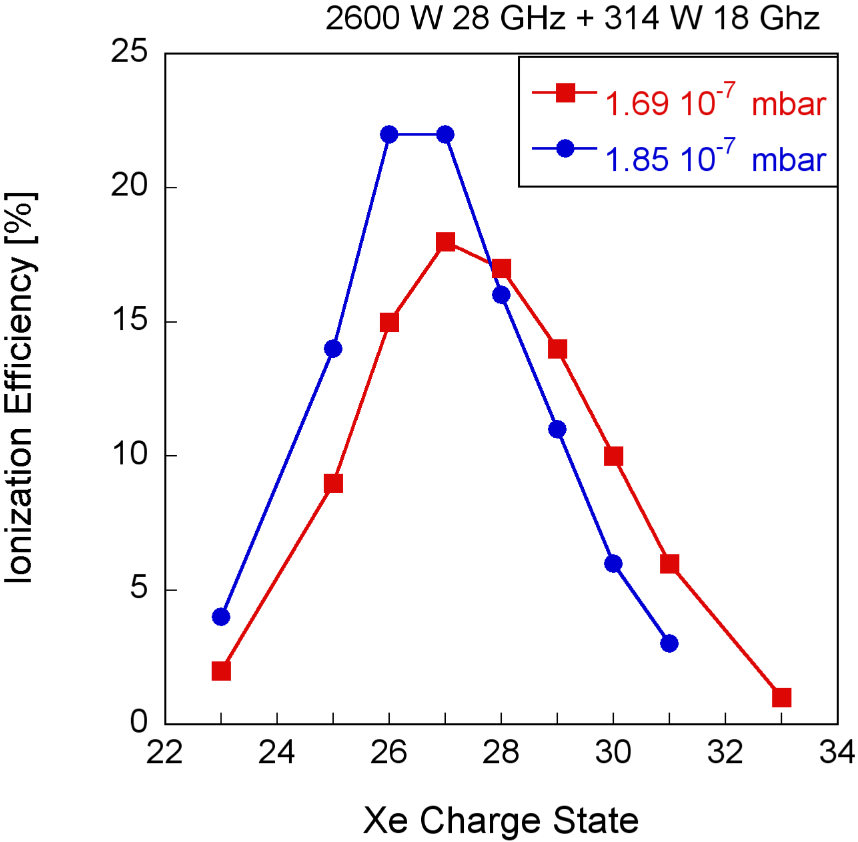
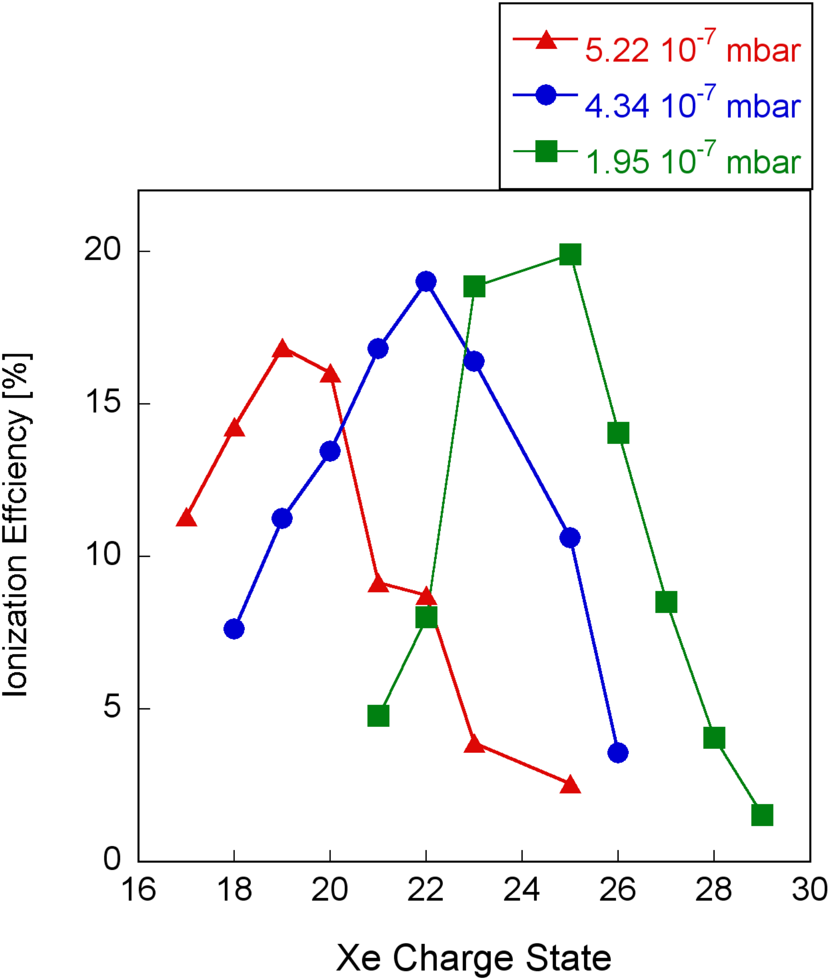
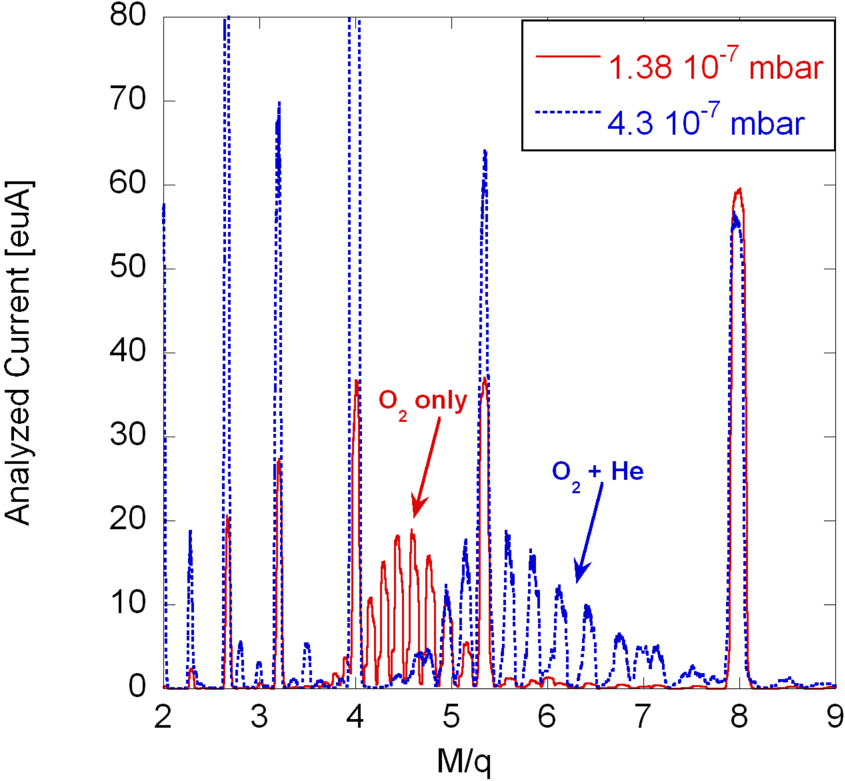
300
250
200
150
100
50
0
Analyzed current [euA]
0
1
2
3
4
5
6
7
8
Oxygen CS
3000 W 28 GHz
Bias connected
2900W 28 GHz
2600W 28 GHz
+356W 18 GHz
(a)
Bias Disk connected
and optimized
Bias Disk removed
(b)
(c)



Ionization Efficiency [%]
Xe Charge State
0
5
10
15
20
22
24
26
28
30
32
34
36
38
● 1.38 10^{-7} mbar
■ 2.09 10^{-7} mbar
▲ 2.70 10^{-7} mbar


2600 W 28 GHz + 314 W 18 Ghz
1.69 10-7 mbar
1.85 10-7 mbar
Ionization Efficiency [%]
Xe Charge State
0
5
10
15
20
25
22
24
26
28
30
32
34


5.22 10^{-7} mbar
4.34 10^{-7} mbar
1.95 10^{-7} mbar
Ionization Effciency [%]
0
5
10
15
20
16
18
20
22
24
26
28
30
Xe Charge State


Analyzed Current [euA]
0
10
20
30
40
50
60
70
80
M/q
2
3
4
5
6
7
8
9
1.38 10^{-7} mbar
4.3 10^{-7} mbar
O_2 only
O_2 + He