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MODELLING OF THE ECR SULPHUR SOURCE

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ABSTRACT

A MINIMAFIOS type ECR ion source is being used for S^{12+} injection into the CERN injector chain for physics experiments at the Super Proton Synchrotron (SPS). In this paper, charge state distribution spectra obtained from the source are studied and, in addition, the possibility of improving the source performance by various methods is explored.

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I. INTRODUCTION

The use of Electron Cyclotron Resonance (ECR) technique, for producing multiply charged ions was first proposed by Postma¹ and following the construction of MAFIOS source by Geller², ECR ion source became a potential candidate for obtaining highly charged ions. Over the past two decades, the performance of ECR ion sources has been improved by adopting one or more of the following methods (i) reducing the number of stages i.e., from double to single stage³, (ii) better confinement in the radial direction⁴, (iii) operating at higher microwave frequency⁵, (iv) using an electron injector at the input stage⁶, (v) biasing a probe with respect to the plasma chamber⁷, (vi) adding light ions into the plasma^{5,8} (vii) operating at $\omega_{ce} \sim 2\omega_{rf}$, where ω_{ce} , ω_{rf} are the electron cyclotron and microwave frequencies respectively⁹ and (viii) operating in the afterglow mode in the case of pulsed sources¹⁰. The ECR ion sources have the capability of producing reasonable currents of highly charged ions with low beam emittance and energy spread. Thus ECR ion sources are now widely used in accelerators and atomic physics facilities¹¹.

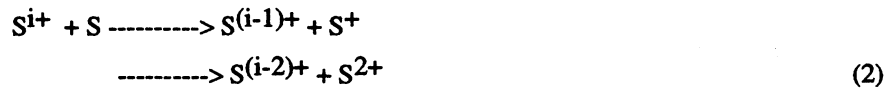
In an ECR ion source, a cold plasma with low charged state ions is injected into the minimum magnetic field region (magnetic trap) which is formed by the combination of radial and axial magnetic fields. Here the electrons are heated by a microwave field whose frequency coincides with the cyclotron frequency of the electrons in the magnetic field of the trap. Multiply charged ions are created in the hot plasma by step by step electron impact ionization. The electrons make Coulomb collisions with charged particles and, due to the small angle scattering, the electrons fall in the loss cone and then escape from the trap. Ions follow the electrons because of ambipolar electric field. The Ion flux is a function of n_i/τ_i , where n_i and τ_i are the ion density and confinement time respectively. The ion confinement time is a crucial parameter, if τ_i is short, ions do not have time to reach high charge state and if τ_i is too long, the high charge states decay by charge exchange instead of being extracted. The ion confinement time is mainly dependent on the density of all the components of the plasma, the electron and ion temperatures, diffusion velocity and plasma potential.

At CERN, a MINIMAFIOS type¹² ECR ion source (15GHz) is being used for S^{12+} injection into the injector chain for physics experiments in the SPS. Prior to this, another ECR source¹³ (10GHz) was used for the injection of O^{6+} . During the sulphur ion production, a light gas is injected into the hot plasma and due to the ion cooling effect, the quantity of S^{12+} is expected to be higher. Oxygen is used as the light gas in the sulphur

source. Since, the Proton Synchrotron Booster (PSB) does not see the difference between O^{6+} and S^{12+} , both of them are accelerated and injected into Proton Synchrotron (PS), where during the passage of transition energy oxygen or sulphur is separated out of the beam¹⁴. The choice of oxygen as the light gas helps to meet the lower current limit needed in PSB for satisfactory acceleration. The sulphur current is optimized by varying the gas mixing ratio, the microwave power and the magnetic fields. In general, the construction and the operation of ECR ion sources are still based on certain rules of thumb derived from the past experience, and by the qualitative understanding of the source behavior. However, a better understanding of the physical processes involved in the source will help one to improve the performance of the source. The present work was carried out to try to understand the results obtained in the sulphur source and in addition, to explore the possibility of improving the source performance. The calculation of mean charge state distribution (CSD) in ECR ion sources was carried out by Jongen¹⁵ and later by Bliman¹⁶, West¹⁷ and Shirkov¹⁸. In all these calculations, the CSD was calculated for a single species, whereas in the present calculation the CSD is calculated simultaneously for two or three different species. Later, a brief account of how our model differs from the earlier ones will be mentioned. Detailed results are presented on the effect of oxygen mixing in sulphur CSD spectrum.. A comparative study on S^{12+} in the total current for different sulphur feeds is carried out. In addition, the study also includes the CSD spectrum as a function of plasma density and electron temperature

II. BALANCE EQUATIONS

In our model, it is assumed that the creation and loss of a particular charge are by single and double ionization and by single and double charge exchange processes as in Ref.16. Multiple ionization and charge exchange, and dielectric recombination are unimportant for the ECR plasmas of our interest. Radiative recombination becomes important at the higher charge state $Z > 20$. The basic mechanisms involved for sulphur are as follows



For the processes involved with oxygen, the above equations can be rewritten by interchanging sulphur and oxygen. The single and double ionization processes are given in Eqn.(1). The single and double charge exchange processes among the species of same type and with different species are given in Eqns. (2) and (3) respectively. The change in ion density of a particular charge "i" with time may be written as

$$\begin{aligned} (dn_i/dt) = & \text{(rate of formation and loss due to atomic processes)}_i \\ & + \text{(the input flux from the first stage)}_i \\ & - \text{(output flux)}_i \end{aligned}$$

So, the general equation for the rate of change of sulphur ions with oxygen as the mixing gas can be written as

$$\begin{aligned} dn_i^s/dt = & \{ (\sigma_{i-1}^I n_{i-1}^s + \sigma_{i-2}^{2I} n_{i-2}^s) n_e v_e + (\sigma_{i+1}^{ex}(S,S) n_o^s + \sigma_{i+1}^{ex}(S,O) n_o^0) v_{ion}^s n_{i+1}^s \\ & + (\sigma_{i+2}^{2ex}(S,S) n_o^s + \sigma_{i+2}^{2ex}(S,O) n_o^0) v_{ion}^s n_{i+2}^s + (v_{ion}^s/L) n_i^s (1) \} \\ & - \{ (\sigma_i^I + \sigma_i^{2I}) n_e v_e + (\sigma_i^{ex}(S,S) n_o^s + \sigma_i^{ex}(S,O) n_o^0 + \sigma_i^{2ex}(S,S) n_o^s \\ & + \sigma_i^{2ex}(S,O) n_o^0) v_{ion}^s + (1/\tau_i^s) \} n_i^s \end{aligned} \quad (4)$$

where n_i^s , n_e , n_o^s , n_o^0 are sulphur ion density with charge state "i", plasma density, neutral sulphur density and neutral oxygen density in the plasma respectively. v_e , v_{ion}^s are the velocities of electron and sulphur ions respectively. τ_i^s is the confinement time of sulphur ions. $\sigma_{i+1}^{ex}(S,O)$, $\sigma_{i+1}^{2ex}(S,O)$ are the single and double charge exchange cross section between sulphur ions with charge "i+1" with neutral oxygen atom respectively. The first and second term in the bracket represent the type of ion and neutral respectively. σ_{i-1}^I , σ_{i-2}^{2I} are the single and double ionization cross section with the final value reaching to the charge state "i" respectively. L is the mirror length. The Eqn.(4) is strictly valid for $2 < i < z-2$, where z is the atomic number of sulphur. For $i=1$ and 2, equation 4 should be modified:

For $i=1$, add term $\sum_{i=1}^{i=z} (\sigma_i^{ex}(S,S) n_i^s v_{ion}^s + \sigma_i^{ex}(O,S) n_i^0 v_{ion}^0) n_o^s$ and substitute $\sigma_{i-2}^{2I} = 0$

For $i=2$, add term $\sum_{i=2}^{i=z} (\sigma_i^{2ex}(S,S) n_i^s v_{ion}^s + \sigma_i^{2ex}(O,S) n_i^0 v_{ion}^0) n_o^s$ where v_{ion}^0 is the thermal velocity of oxygen ion.

Substitute $n_{i+2} = \sigma_{i+1}^{2I} = 0$ for $i=z-1$ and $n_{i+1} = n_{i+2} = \sigma_{i+1}^{2I} = \sigma_{i+1}^I = 0$ for $i=z$. For oxygen ions the Eqn.(4) can be rewritten by interchanging sulphur and oxygen.

In the hot plasma, there is a continuous burn up of neutrals of oxygen and sulphur through electron-impact ionization and charge exchange with ions. In addition, there is a continuous neutral flux entering and leaving the plasma. It is to be noted that the mean free path for particle-particle collisions is large compared with the chamber dimensions and for this reason, the neutrals are expected to acquire the temperature of walls and not the ion temperature. The change in sulphur neutral density with time can be written as

$$\begin{aligned}
dn^S_O/dt = & \{ n^S_1 \sigma^{ex}_1(S,O) n^O_0 + n^S_2 \sigma^{2ex}_2(S,O) n^O_0 \} v^S_{ion} + (S/V) v^S_0 n^S_{ext} \\
& - [(\sum_{i=2}^{i=z} \sigma^{ex}_i(S,S) n^S_i + \sum_{i=3}^{i=z} \sigma^{2ex}_i(S,S) n^S_i) n^S_0 v^S_{ion} \\
& + (\sum_{i=1}^{i=z} \sigma^{ex}_i(O,S) n^O_i + \sum_{i=2}^{i=z} \sigma^{2ex}_i(O,S) n^O_i) v^O_{ion} n^S_0 \\
& + (\sigma^I_O + \sigma^{2I}_O) n^S_0 n_e v_e + (S/V) v^S_0 n^S_0 \} \quad (5)
\end{aligned}$$

where n^S_{ext} is the sulphur neutral density outside the plasma. A similar equation can be written for oxygen neutrals. The charge neutrality of plasma needs an additional equation as follows

$$\sum_{i=1}^{i=z} i n^S_i + \sum_{i=1}^{i=z} i n^O_i = n_e \quad (6)$$

It is assumed that all processes in the source are stationary and so the change in density of ions of different charge states and neutrals in time can be chosen to be zero. The complete set of equations, $dn^S_i/dt = dn^O_i/dt = dn^S_O/dt = dn^O_O/dt = 0$ together with the equation for charge neutrality is solved as a set of nonlinear algebraic equations by an iterative method. For single ionization, we have used the simplified Lotz's formula^{19,20}. The ionization and sub-shell binding energies have been taken from Ref.21 and 22 respectively. For double ionization, the expression of Muller et al²³ is used. For charge exchange cross sections which involve the species of same type and of different types, the approximated formulae from Ref.24 are used.

III. CONFINEMENT TIMES

The ion confinement time is determined by the ambipolar diffusion of the ions and the ion mobility in the electric field established by the plasma potential^{15,18}. The general form of ion confinement time can be written in as

$$\tau_i = l^2 / \{ D_i (1 + iV/T_i) \} \quad (7)$$

where R is the mirror ratio, V is the plasma potential, D_i is the diffusion coefficient and $l=L/2$.

$$V = \frac{n_e l^2 / 4 \tau_e - \left(\sum_{i=1}^{i=z_s} n_i^s i D_i^s + \sum_{i=1}^{i=z_o} n_i^o i D_i^o \right)}{\sum_{i=1}^{i=z_s} n_i^s i^2 D_i^s / T_i + \sum_{i=1}^{i=z_o} n_i^o i^2 D_i^o / T_i} \quad (8)$$

where D_i^s and D_i^o are the diffusion coefficients of sulphur and oxygen ions.

It is assumed that the electrons are heated by microwave power and their life time is basically determined by scattering of elastic collisions with electrons, ions and neutral atoms. So the electron confinement time can be written as

$$\tau_e = 1 / (\nu_{ee} + \nu_{e\sum i} + \nu_{e\sum n}) \quad (9)$$

where ν_{ee} , $\nu_{e\sum i}$, $\nu_{e\sum n}$ are the elastic collision rates of electron-electron, electron-ion, electron-neutral respectively. The expressions for these terms have been used from Ref.17 and 25.

IV. ION TEMPERATURE

The ions are being heated by energetic electrons through elastic Coulomb collisions and it is expected that both sulphur and oxygen ions of different charge states will attain a unique ion temperature T_i , due to ion-ion elastic collisions. The change in mean energy of ion can be written on the basis of Spitzer's relaxation time²⁵ as follows

$$\langle dT_i / dt \rangle = \frac{(T_e - T_i)}{\tau_{eq}} \quad (10)$$

where τ_{eq} is the lowest equipartition time. At the equilibrium condition, it is possible to define the ion temperature as

$$T_i = \frac{\langle dT_i / dt \rangle \left(\sum_{i=1}^{i=z_s} n_i^s + \sum_{i=1}^{i=z_o} n_i^o \right)}{\sum_{i=1}^{i=z_s} n_i^s / \tau_i^s + \sum_{i=1}^{i=z_o} n_i^o / \tau_i^o} \quad (11)$$

In principle, one should take the net increase in ion energy due to the atomic processes and it was seen in our calculation that this factor was small and so it is not included in T_i .

V. EXTRACTION OF IONS

The output ion current of sulphur of charge state "i" can be written as¹⁷

$$I_i^S = i n_i^S e l / \tau_i^S \quad (12)$$

where e is the electronic charge. For the total output current in the above equation, oxygen current of a particular charge having same charge to mass ratio of sulphur is added. The output current is normalized to the peak current and only the normalized current is presented in the results.

VI. COMPUTATIONAL METHODS

Fig.1 schematically explains how we obtain the normalized output current. The code is used to fit the results obtained from our ECR sulphur source parameters and the important parameters are summarized in Table.1. Like in the earlier models¹⁵⁻¹⁸, the input flux from the first stage is not included in the present calculation. The code is written such that it can be run with and without gas mixing. Since, we do not have exact knowledge of plasma parameters of the source, we have to derive these values from the known experimental parameters. From the past experience, it is seen that the source is stable only when it is operated with a plasma density which is lower than the density corresponds to the cut-off frequency and so the plasma density (n_e) is assumed to be $2.4 \times 10^{12} \text{ cm}^{-3}$. The input microwave power to the source gives an indirect idea about the electron temperature. Mainly, the microwave power is being spent in radiation, scattering of electrons and ionizing the atoms. Usually, the power loss in radiation is small relative to the other power sinks. The expression for power from Ref.17, is used for calculating the microwave power. The input microwave power is spent in pre-ionization in the first stage and in ionization in the second stage of the source. It is assumed that only two-third of the total power is being spent in the second stage and the electron temperature is fixed by matching the RF power calculated from the code. From the base pressure and the flow rate, it is possible to estimate the neutral densities, but again it will be an approximate value, since it is difficult to estimate the pumping speed and the degassing rate. The neutral densities are chosen to a set of value which satisfies n_e . It is to be noted that the error in the code may come mainly from the input experimental data and the approximate formulae used for calculating the various cross sections.

VII. RESULTS AND DISCUSSIONS

Initially, the code was run to understand the results obtained from our ECR source. Two typical output CSD spectrums together with the code results are presented in Figs 2 and 3. It should be noted that the experimental spectrum was taken when the source was optimized for S^{12+} operation and there is an overall agreement between the code results and the experimental points. To understand the oxygen role, the CSD spectrum of sulphur was studied with different ratios of sulphur and oxygen and the results are presented in Fig.4. It is seen from the figure that the sulphur CSD spectrum shifts to the highly charged ions, in the presence of oxygen. By ion-ion collisions, oxygen takes away part of the total energy from the plasma and then this decrease the total mean energy of ion temperature. This sets a high ion life time for higher charge state of sulphur. In addition, by the charge exchange processes, oxygen ions give rise to sulphur ion of charge state 1 and 2, which increase the density of highly charged sulphur ion by step by step ionization. Another characteristic property associated with our source is the total current in which S^{12+} and O^{6+} are presented. From the theoretical calculations, the estimated value of S^{12+} current in the total current is nearly ~ (15-20)%, which is in good agreement with our experimental observation.

The code was run together with a supporting gas (hydrogen or carbon) and it should be pointed out that sulphur can be injected into the plasma as H_2S or CS_2 . In the carbon case, the sulphur content in the total current increased as much as 30%, but the total current decreased by ~20%. From the source operational point of view, not only should we have good sulphur current, we should also have good total current. This leads to the conclusion that by changing the feed gas from H_2S to CS_2 , there will not be much advantages and in addition CS_2 feed requires better pumping systems.

The variation of CSD as a function of electron temperature and plasma density are studied. The normalized sulphur current for different charge state for the electron temperature of 3,5 and 7 keV are presented in Fig.5. The CSD spectrum shifts towards the higher charge state at higher electron temperature. When the electron temperature is raised, the ionization term for the higher charge state increases and hence the spectrum shifts towards the higher charge state. Increasing the electron temperature simultaneously brings down the ionization term of low charged state which are necessary for the flux of highly charged ion in the step by step ionization processes. So, only in the higher charge state, $Z > 10$, the ion current is increased. This suggests that there should be a different optimum temperature for obtaining maximum current for each charge state.

The sulphur ion current for different charge states for the plasma density of $n_e \sim 1.2 \times 10^{12} \text{ cm}^{-3}$ and $2.4 \times 10^{12} \text{ cm}^{-3}$ corresponding to the microwave frequency of 10GHz and 15GHz, at the electron temperature 5keV is studied. It is observed that the nature of CSD spectrum is almost the same for both the cases, as in Ref.16. At the same time, it should be noted that the S^{12+} current for 15GHz is nearly 4 times higher than the 10GHz case. So, in general, one would expect that by increasing the microwave frequency, one can obtain a higher ion current of higher charge state. From the MINIMAFIOS results²⁶, it is confirmed that the ion current of higher charge state increases, when the source was operated with higher frequency microwave source. However, this requires a higher magnetic field to satisfy the resonance condition ($\omega_{ce} \sim \omega_{if}$).

In the present calculation, the thermal electron population is not considered and in fact this might be the reason that the code results differ in the lower charge state as indicated by Fig.2 and Fig.3. The electron impact ionization cross section for low charge state is less from the hot electron component. So, thermal electrons are necessary for the population of low charge state and because of the step by step ionization processes, this may play an important role for the flux of highly charged ions. The various possible ways of getting thermal electrons are (i) injection from the first stage plasma (ii) injection from an electron gun (iii) generation by the atomic processes and (iv) secondary emission (wall coating or biasing a probe). Detailed theoretical calculation is essential to understand the effect of thermal electrons from each contribution in the CSD spectrum of ECR source.

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TABLE.1 IMPORTANT PARAMETERS OF THE ECR SOURCE

Microwave frequency	: 15GHz
Mirror length	: 30cm
Chamber diameter	: 7.0cm
Mirror ratio	: 2.0

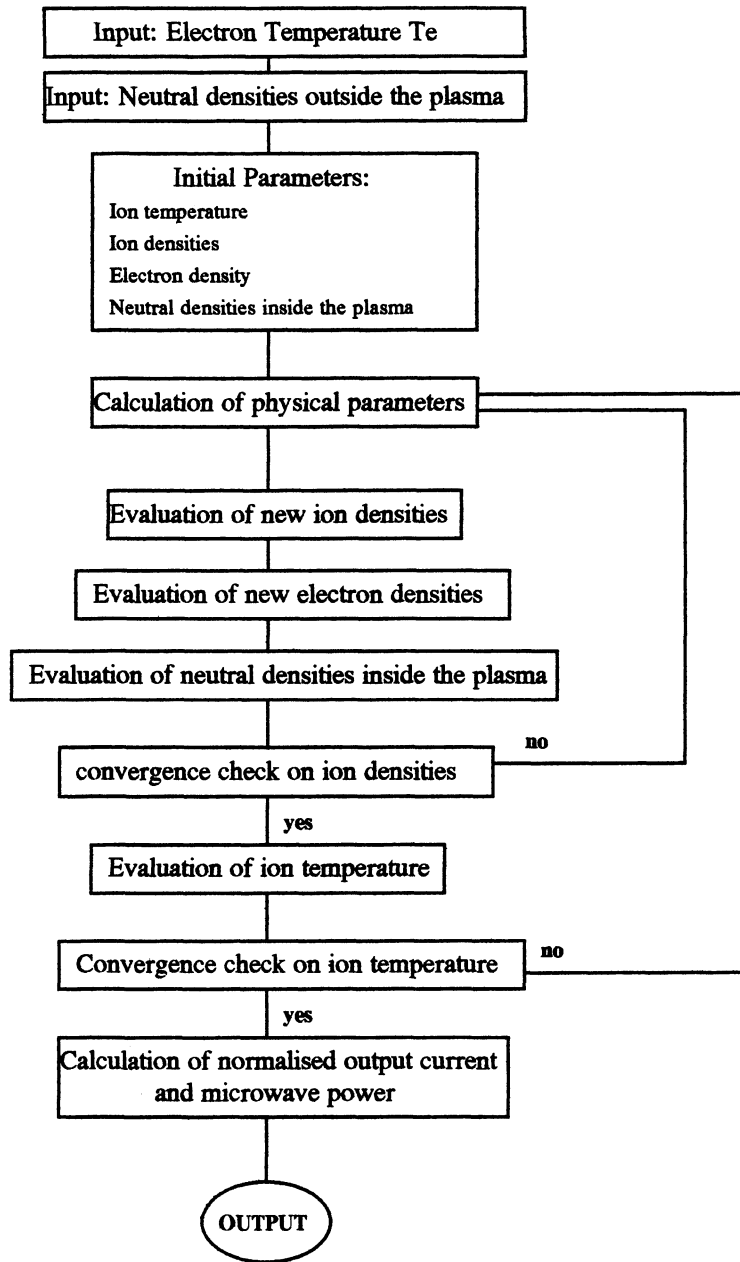


Fig.1 Schematic diagram of the computational method

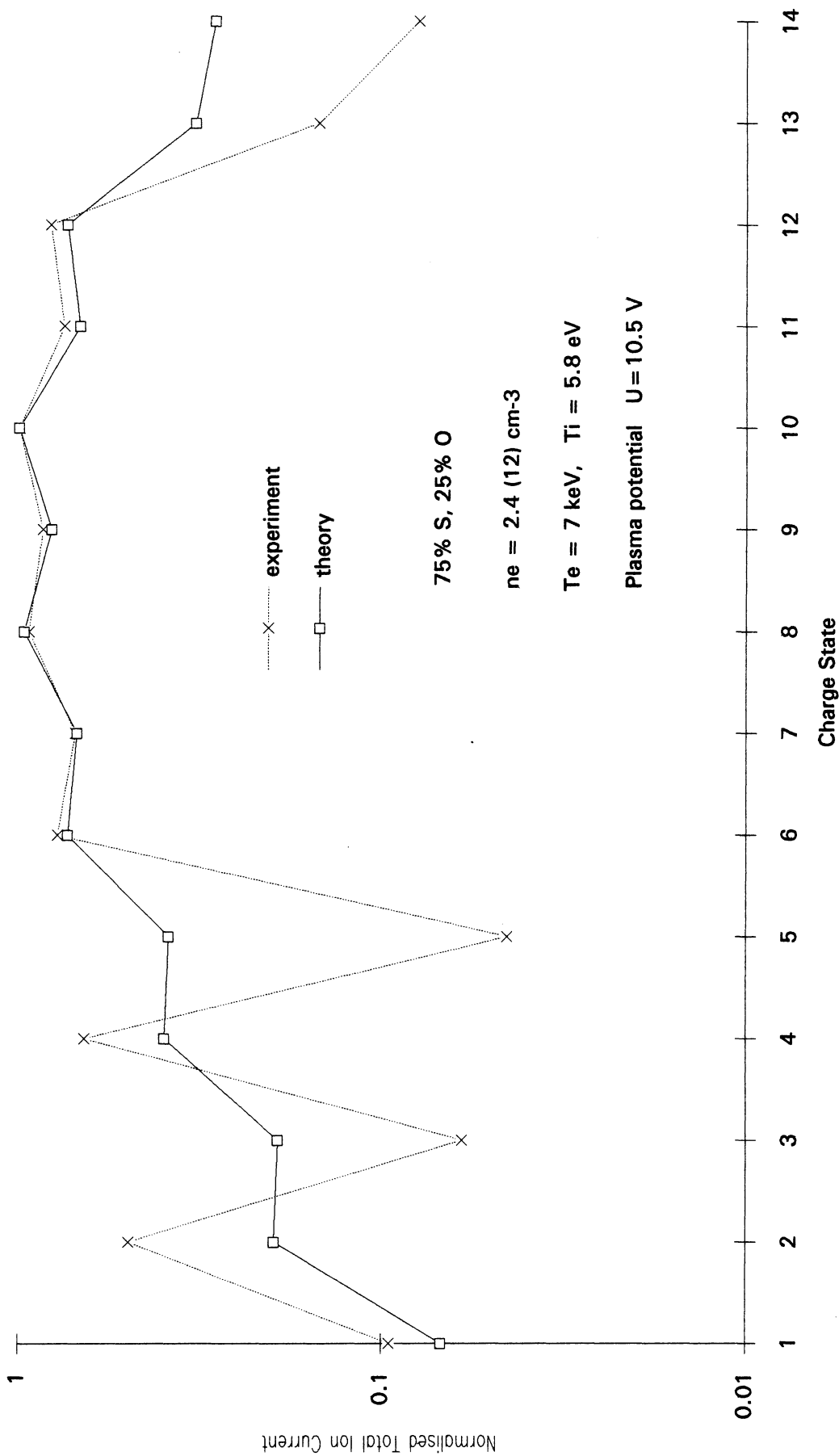


Fig.2 A typical experimental CSD spectrum (oxygen + sulphur) together with the code results for the sulphur peaking at the charge state 10 +

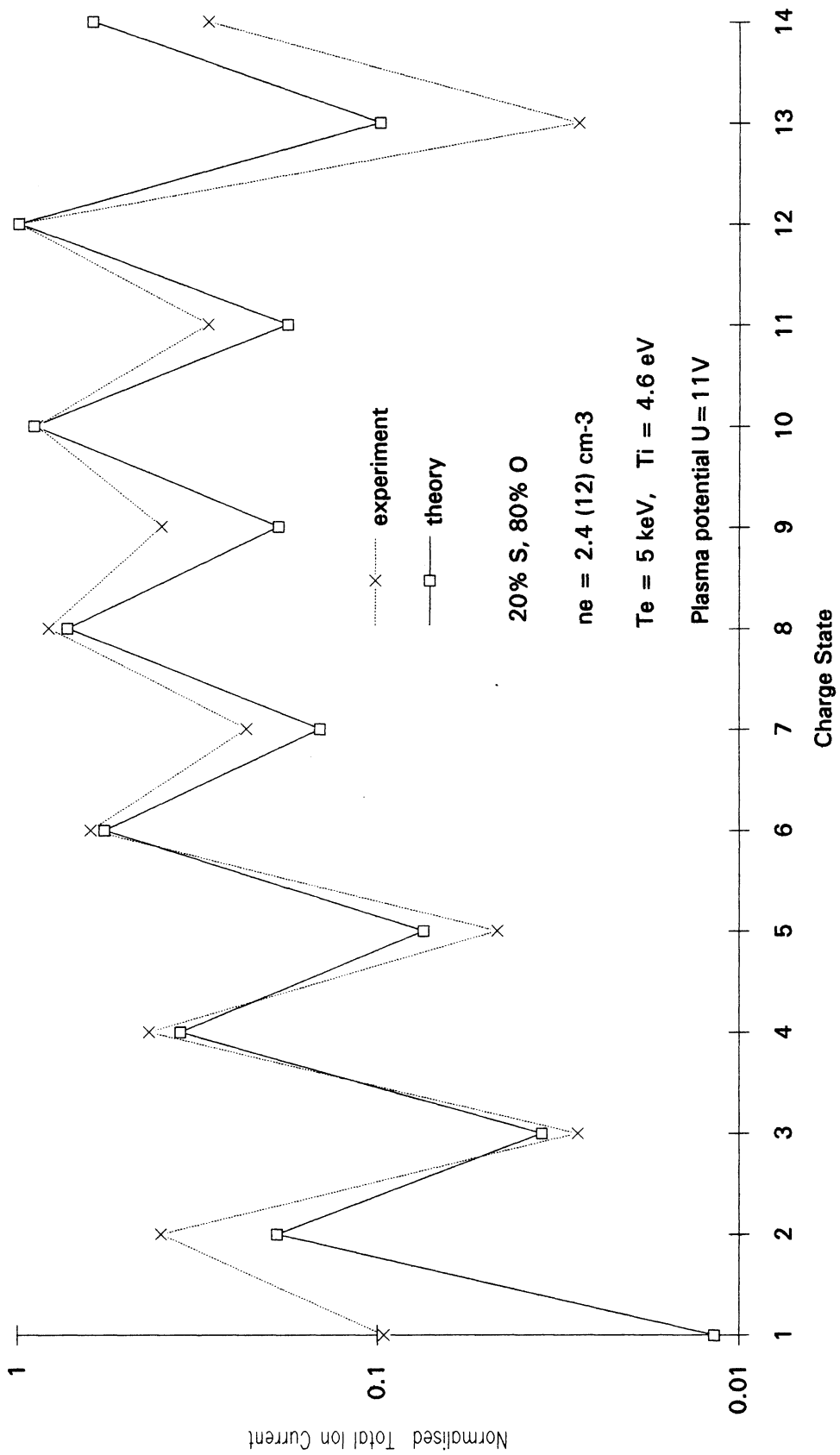


Fig.3 A typical experimental CSD spectrum (oxygen + sulphur) together with the code results for the sulphur peaking at the charge state 12 +

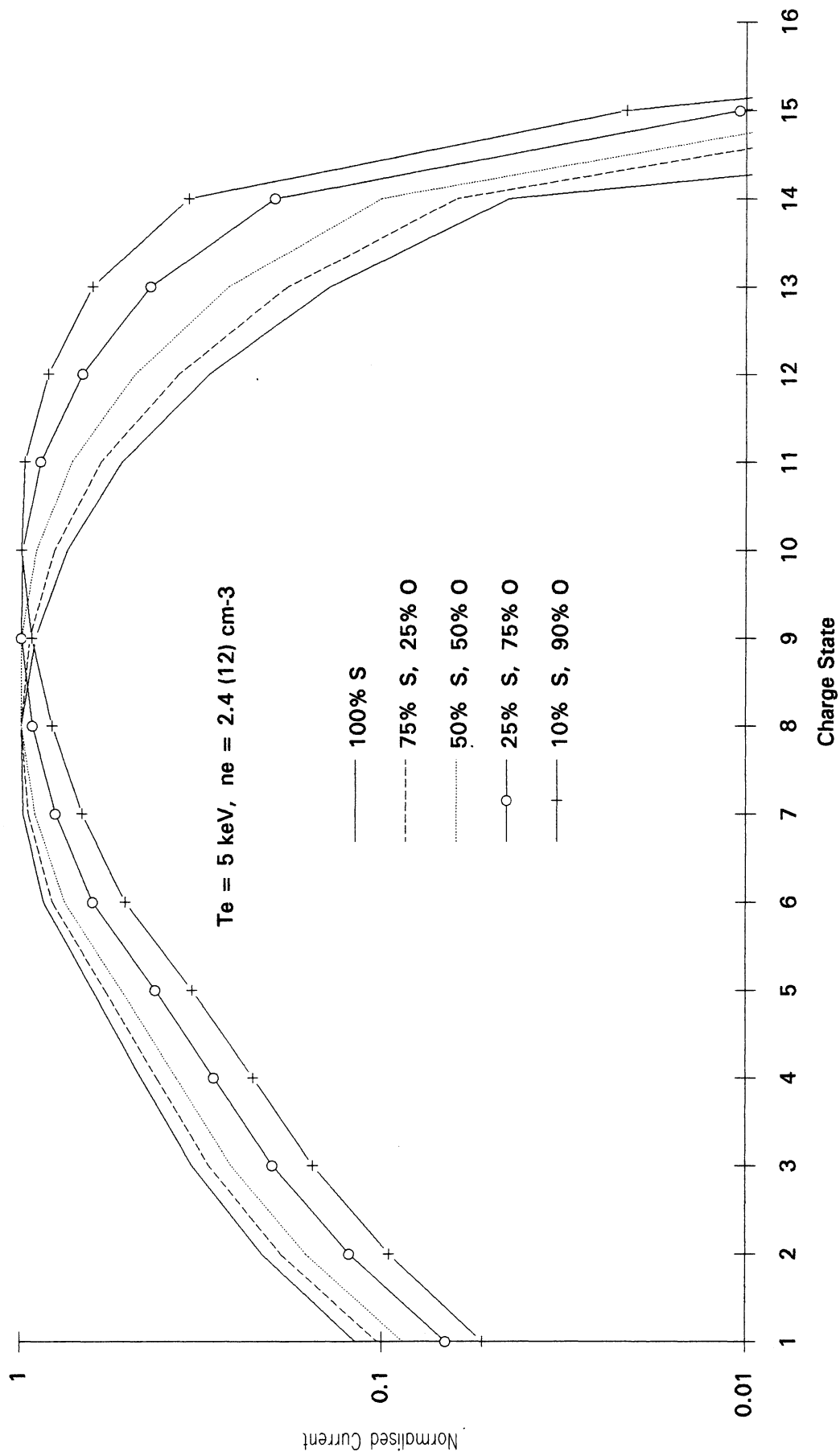


Fig.4 The CSD spectrum of sulphur for various ratios of the mixing gas

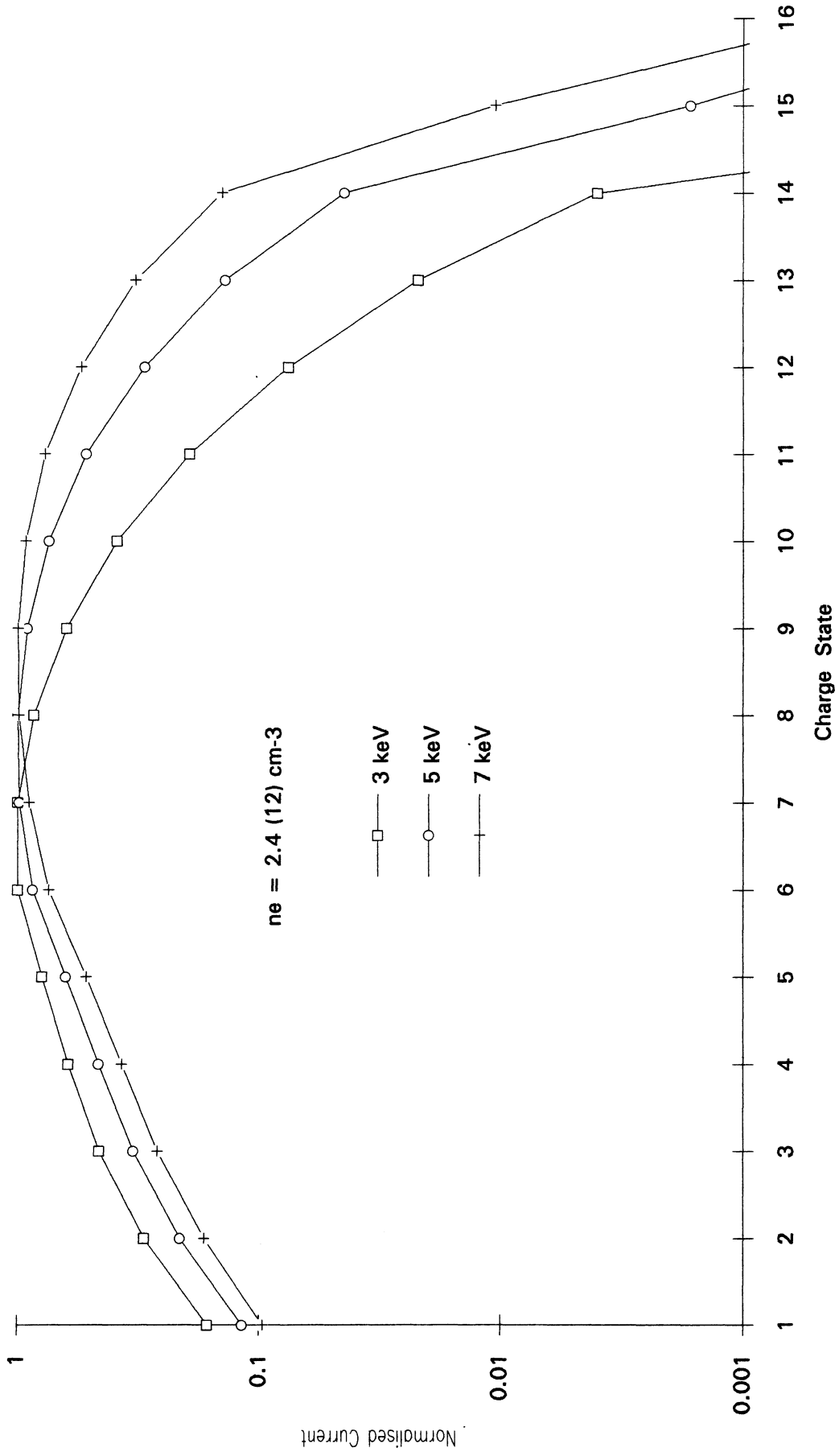


Fig.5 The normalized sulphur current for different charge states for the electron temperature of 3,5 and 7 keV