

FREQUENCY TUNING EFFECT ON THE BREMSSTRAHLUNG SPECTRA, BEAM INTENSITY AND SHAPE IN AN ECR ION SOURCE

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Abstract

The effect of the frequency tuning on bremsstrahlung spectra, beam intensity and shape in the 10 GHz, Nanogan ECR ion source have been investigated. The main aim of this work was to study the effect on a lower frequency type of ECR source where the separation between various modes in the cavity is much larger. The warm and cold components of the electrons were observed to be directly correlated with the beam intensity enhancement in the case of Ar⁹⁺ but not so for O⁵⁺. However, the warm electron component was much smaller than the cold component. The beam shapes of O⁵⁺ measured as a function of frequency showed a strong variation without hollow beam formation. Due to the use of an octupole magnetic structure in the Nanogan ECR source, the quadrupolar structure of the ECR surface is modified with the frequency tuning. In general, we have observed a strong absorption of microwave power at various frequencies whenever the reflection co-efficient showed a minimum value and the effect was seen stronger for the higher charge states. Details of the measurements carried out on the bremsstrahlung spectra, beam intensity and shape are presented together with the results of simulations.

INTRODUCTION

Experiments carried out using various ECR ion sources have shown that even a slight change in the frequency in the order of MHz strongly influences the beam intensities, shape, emittance, brightness and stability. The extracted currents are sensitive to small changes of less than 1 % in the rf frequency. This technique which has been called as the frequency tuning effect [1] was pioneered by the ECR group in Catania. Due to the remarkable change in the beam characteristics, the quality of the beam can be improved further. In the field of ECR ion source development, there is a constant endeavour to improve the beam quality and intensity. Earlier works using the frequency tuning effect have shown the influence on the beam characteristics [2-5] with a clear variation in the beam quality and intensity as a function of frequency. In a few of the experiments performed, the formation of hollow beam was observed just after source extraction before the solenoid focusing element [3]. Understanding of the bremsstrahlung spectrum of cold, warm, and hot electrons, and the electron distribution function are also necessary to study how characteristics of the beam are

influenced by the frequency tuning. S. Gammino *et al.* [6] have shown that the number of energetic electrons which populates the spectrum tail slightly changes when passing from one frequency to the other mostly because of variation in the warm population density. The slope of the bremsstrahlung spectra was observed to remain unchanged. But the experimental results shown in Ref. 7 did not show the trend where-in a large number of x-rays seemed to correspond to higher $\langle q \rangle$ and more intense beam current. For further understanding the frequency tuning effect on the beam characteristics and on the plasma conditions inside the cavity, it was felt necessary to study this effect on a lower frequency type of ECR ion source where the separation between various modes in the cavity is much larger than that of a source operating at a higher frequency. In hybrid modes, due to the superposition of two or more modes, it becomes difficult to explain how the electromagnetic fields can influence the production of beam intensities of highly charged ions. In this case, the measurement of the bremsstrahlung spectrum may give further information on the distribution of cold and warm electrons which can explain the probable ionization processes responsible for producing higher intensities of highly charged ions. At the Inter University Accelerator Centre, a compact, permanent magnet, 10 GHz Nanogan ECR ion source was used [8] to study the frequency tuning effect on the beam intensity, shape, and bremsstrahlung spectrum [9]. In order to further understand the frequency tuning effect on the beam characteristics, 3D simulations of the complete magnetic structure and of the electromagnetic fields for various modes in vacuum of the ECR cavity using CST Microwave Studio have been carried out [10]. To determine the shape of the beam at various tuning frequencies, the CST particle tracking solver was used under the combined influence of the confining magnetic fields and the electromagnetic fields of the cavity for specific modes. These simulations are compared to the beam shapes observed experimentally at various tuning frequencies. Presently, the simulation of one of the dominant modes of the cavity is compared with the observed beam shape at the corresponding frequency.

EXPERIMENTAL SET-UP

A 10 GHz fully permanent magnet, Nanogan ECR ion source was powered by a wide-band (8–18 GHz) travelling wave tube (TWT) amplifier manufactured by Amplifier Research, U.S.A [11]. A Rhode and Schwarz signal generator was used to vary the frequency and in the case of our experimental study, the frequency was chosen

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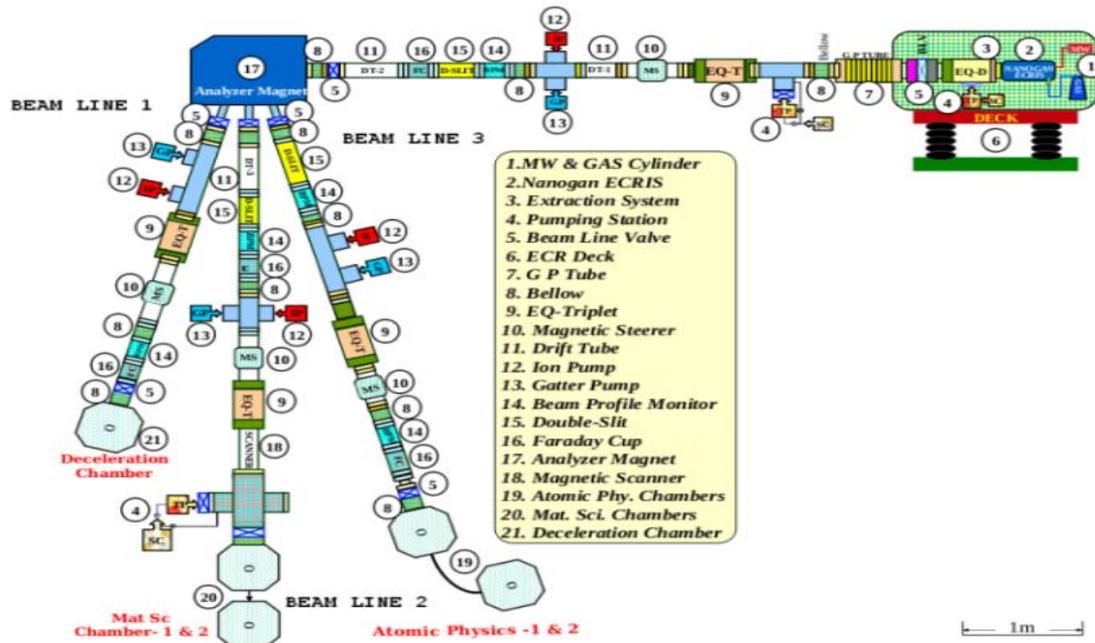


Figure 1: View of the ECR ion source and beam line 2 used for the frequency measurement.

to be varied from ~ 9.5 to 10.5 GHz with a stable mode operation of the plasma over the whole frequency range. A schematic of the ECR ion source and the experimental beam-lines is shown in fig. 1. The plasma chamber has an inner diameter of 26 mm and length 140 mm coupled to an RF cube and a bias tube is positioned inside the plasma chamber for supplying cold electrons to the plasma. The plasma chamber and the bias tube made of copper are air-cooled during normal source operations. The coupling of the electromagnetic waves to the ECR cavity is achieved by using a co-axial transmission line operating in the TEM mode [12] and traditionally used in all Caprice type of ECR ion sources.

a 3 in. \times 3 in. NaI detector positioned at the injection side of the 10 GHz Nanogan ECR source placed at a distance of ~ 70 cm with proper collimation to measure only the bremsstrahlung coming from the ECR plasma (see fig. 2). It should be mentioned that the bias tube was used in this measurement to observe its effect on the frequency tuning. Due to the presence of a copper heat sink (for the bias tube) along the line of sight of the emitted bremsstrahlung, the observed count rates were attenuated. Each of the measured spectra at a particular frequency was counted for 3600 seconds. For calculations of the various modes of the ECR cavity and for tracking the electron motion, a model of the magnetic structure and the ECR cavity was built using CST microwave studio and is shown in fig. 3.

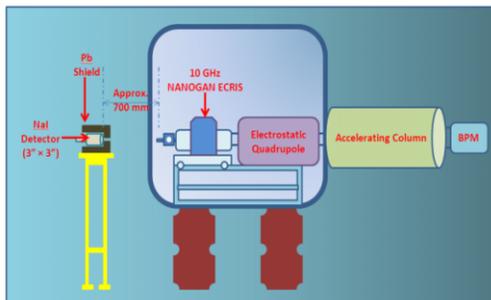


Figure 2: Schematic of the set-up to measure the x-rays from the 10 GHz Nanogan ECR ion source.

The 10 GHz Nanogan ECR ion source is a fully permanent magnet, therefore, the tuning parameters of the source are limited to controlling the gas flow rate and the RF power into the plasma chamber. In all the experiments reported below, the single-stub RF tuner position was fixed at an optimum position for minimizing the reflected power. The bremsstrahlung spectra were measured using

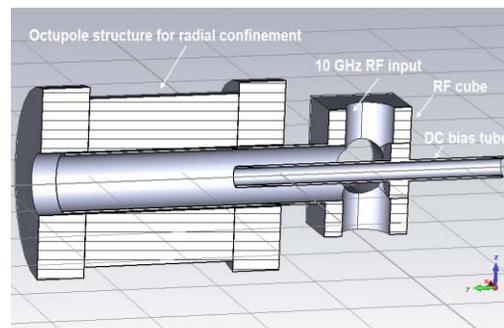


Figure 3: View of the model of the magnetic structure together with the ECR cavity built using CST microwave studio.

Considering the ECR cavity with a radius of 13 mm and length 140 mm, all possible modes in the frequency range of 9 to 11 GHz have been calculated using the standard formula for the TE and TM modes and are

shown in table 1. The closest mode to the main frequency of operation of the source is the TE₁₁₇ mode with a frequency of 10.0914719844 GHz.

Table 1: Calculated frequencies for various modes for the ECR cavity in vacuum.

Mode type	Calculated frequency (GHz)
TM ₀₁₂	9.0823955987
TE ₁₁₆	9.3238928884
TM ₀₁₃	9.3926442931
TM ₀₁₄	9.8105232596
TE ₁₁₇	10.0914719844
TM ₀₁₅	10.3229699816
TE ₁₁₈	10.9102418779
TM ₀₁₆	10.9166750733

Details of the calculated ECR surface at 10 GHz is shown in fig. 4 and the actual cavity of the ECR ion source including the bias tube coupled to the RF cube is shown on the left side of fig. 5.

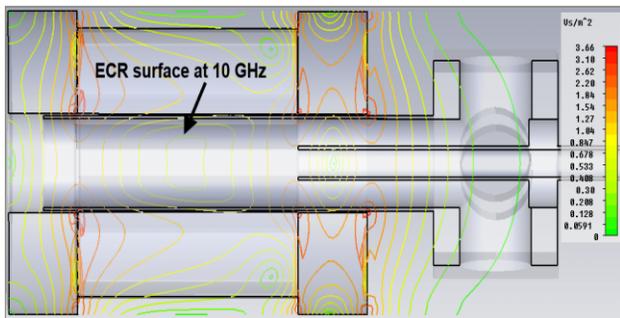


Figure 4: View of the cross section of the ECR surface at the mid-plane of the cavity

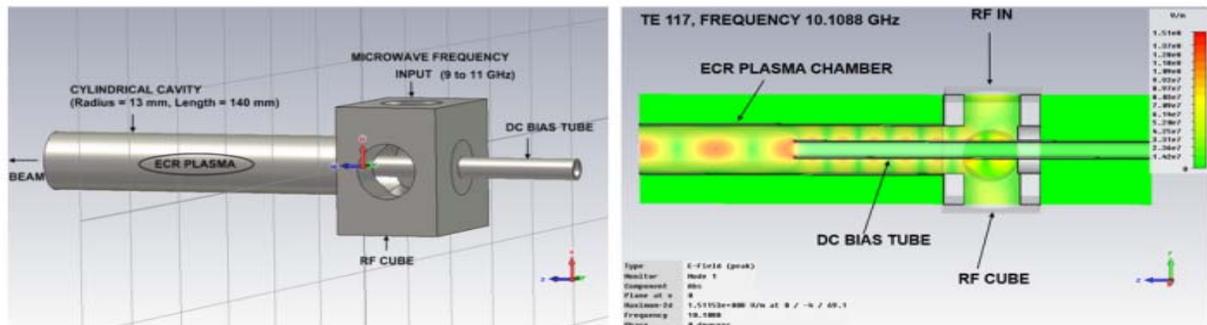


Figure 5: (left) CST model of the ECR cavity coupled to the RF cube (right) one of the simulated dominant modes in vacuum.

The corresponding TE₁₁₇ mode with a calculated frequency of 10.1088 GHz which matches closely to the one calculated by the standard formula and is shown on the right side of fig. 5.

EXPERIMENTAL MEASUREMENTS

The experimental measurements using the frequency tuning effect were performed for two beams, viz., oxygen and argon. In the case of oxygen, the beam tuning was first optimized for O⁵⁺ (280 enA, RF forward power 27 W, reflected power 5 W, gas pressure 8.4×10^{-6} mbar, negative dc bias -88 V, 0.19 mA) at the operational frequency of 10.0 GHz. The frequency was then varied from ~ 9.5 to 10.5 GHz. In fig. 6, the beam currents of oxygen charge states and electron energy distributions were measured as a function of frequency including the reflected co-efficient. In the case of argon, the beam tuning was optimized (70 enA, RF forward power 53 W, reflected power 8 W, gas pressure 5.6×10^{-6} mbar, negative dc bias -118 V, 0.25 mA) on Ar⁹⁺ at the operational frequency of 10.0 GHz. In fig. 7, the beam currents of argon charge states and the electron energy distributions were measured as a function of frequency including the reflection co-efficient. The modes for some particular frequencies where the beam intensities are enhanced have been identified, whereas those frequencies whose modes could not be identified are probably hybrid modes which also contribute to the enhancement of the beam intensities. In the case of oxygen tuning (see fig. 6), the beam current of O⁵⁺ has been enhanced by a factor of 1.46 at a hybrid frequency of 10.14 GHz with respect to 10.0 GHz. Calculated modes at 10.3229699816 GHz (TM₀₁₅) and 9.8105232596 GHz (TM₀₁₄) also show enhancement of beam intensities.

With respect to the warm electron component, no correlation could be observed with the beam intensity enhancement. In fig. 7, the beam current of Ar⁹⁺ has been enhanced by a factor of 1.05 at a hybrid frequency of 10.26 GHz with respect to 10.0 GHz and a correlation between the warm electron component and the beam intensity enhancement is observed.

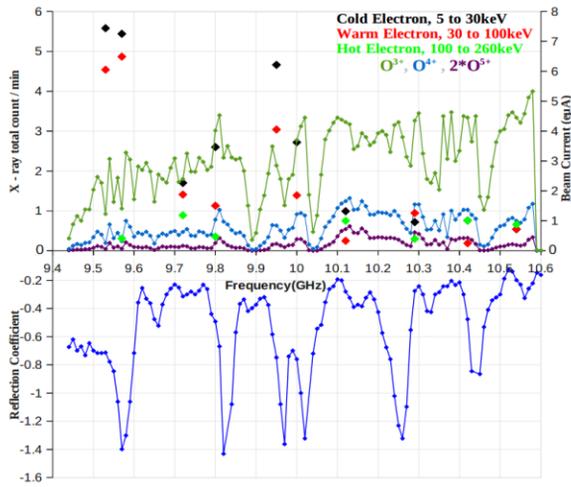


Figure 6: Effect of the various charge states of oxygen, electron energy distributions, and reflection co-efficient as a function of frequency.

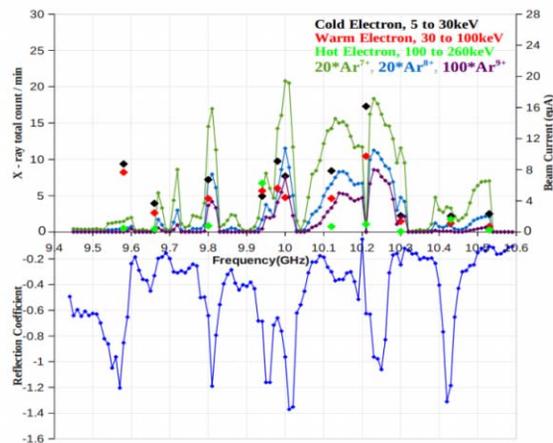


Figure 7: Effect of the various charge states of argon, electron energy distributions, and reflection co-efficient as a function of frequency.

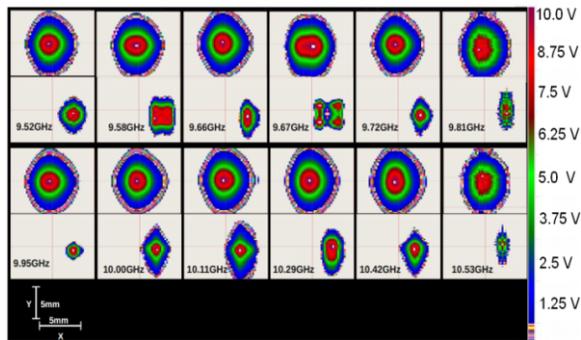


Figure 8: (Top) Measured shape of the beam for oxygen plasma for various frequencies and (bottom) after analysis for O⁵⁺ with their intensities.

The shapes of the beam as a function of frequency in the case of oxygen plasma were measured at the position of the first beam profile monitor, BPM 1 which had a sensitivity of 10⁻⁴ A/V, located after the 300 kV accelerating column and another beam profile monitor after A/q analysis (beam profile monitor, BPM 2 with sensitivity of 10⁻⁶ A/V positioned after the analyzing magnet) for the case of O⁵⁺. A clear variation of the beam shape shown in fig. 8 was seen at both the locations of the beam profile monitors (BPM 1 and BPM 2) when the frequency is changed.

PARTICLE TRACKING

In order to further understand the evolution of the beam shapes as a function of frequency, particle tracking under the combined influence of the confining magnetic field and rf electric field was initiated. For this purpose, the CST particle studio program was used. It incorporates a powerful electromagnetic solver for calculating external fields, it has an efficient particle tracking algorithm and sophisticated emission models that can describe the extraction of particles from active surfaces.

The magnetic structure with cavity shown in fig. 3 was used for particle tracking inside the cavity without considering the effect of the plasma. The space charge limited emission model was used which also depends on the strength of the external field at the emitting surface. The particles are pushed through the computational domain by interpolating the field values to their location and calculating the electromagnetic forces. The dominant mode of the ECR cavity was chosen (shown on the right hand side of fig. 5) for tracking the motion of electrons and to further compare it with the measured distribution of the beam shape at that particular frequency (shown in figure 8, at 10.11 GHz). Fig. 9 shows the evolution of the electrons from the DC bias tube at a voltage of 100 V as viewed from the injection side and showing the quadrupole shape of the plasma. The electrons can quickly gain energy of ~ 600 keV in ~ 7.7 ns. In fig. 10, the shape of the plasma on the extraction side is shown. The simulated shape of the ECR plasma matches well with the measured shape of the beam for the dominant mode. Due to memory limitations on a Windows XP platform, the total number of particles was limited to ~ 30,000. Further developments are in progress.

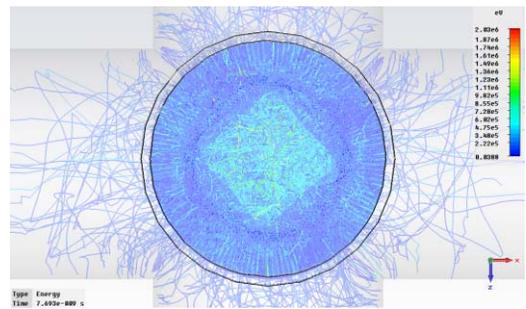


Figure 9: View of the computed electron trajectories at the injection side with initial energy of 100 eV for the dominant mode in vacuum.

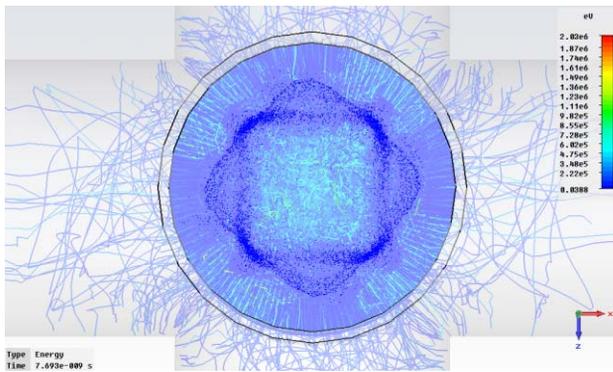


Figure 10: View of the quadrupolar structure of the ECR plasma at the extraction side, computed for the dominant mode in vacuum.

SUMMARY AND CONCLUSION

Considering the measurements for oxygen and argon beams in terms of the beam intensities and the beam shape measurements for oxygen plasma, it is observed that there is a strong absorption of microwave power at various frequencies whenever the reflection co-efficient showed a minimum value and the effect was seen stronger the higher charge states. The shape of the beam as a function of frequency clearly shows a strong variation at BPM 1. The warm and cold components of the electrons were found to be directly correlated with beam intensity enhancement in case of Ar^{9+} but not so for O^{5+} . The warm electron component was, however, much smaller compared to the cold component. The particle tracking in the vacuum mode cavity shows the evolution of the quadrupolar structure of the ECR plasma which is similar to the measurement of the beam shape at the dominant mode with no hollow beam formation. This shows that the electromagnetic field distribution affects the shape of the ECR plasma at a particular mode of operation.

ACKNOWLEDGEMENT

One of the authors (G.R) would like to thank the Department of Science and Technology (DST) for supporting partial financial assistance for travel purposes.

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