A study of the Two-Frequency Effect in ECR2 ion source

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Our efforts have continued to improve the performance of the 14.5 GHz electron cyclotron resonance (ECR) ion source, ECR2. Our primary focus is the study of whether a true two-frequency plasma heating effect can be identified in ECR2, leading to the extraction of more intense, higher charge state ions for acceleration in the K150 cyclotron.

The advantage of simultaneously injecting microwaves of two separated frequencies for plasma heating was first demonstrated by the Lawrence Berkeley National Laboratory (LBNL) group on their advanced ECR ion source (AECR), which operated at 14 GHz (the primary frequency) and 10 GHz (the second frequency) [1]. By comparison with the best results obtained with single-frequency (14 GHz) heating, their measurements performed with two-frequency (14+10 GHz) heating showed that the overall charge state distribution shifted to higher charge states, production of the high charge state ions increased by a factor of 2-5 or higher, and the plasma stability improved. These experimental results strongly support the idea that an increased number of resonance surfaces (instead of one) leads to an enhancement of source performance.

Following the approach taken by the LBNL group, we have used the standard 14.5 GHz microwave injection from a 2.25 kW klystron and the second microwave injection from a 0.5 kW traveling wave tube amplifier (TWTA) with a normal operating range of 11–13 GHz to produce highly charged ions in a two-frequency heating mode. Running both transmitters gives hints of better performance of ECR2 at comparable microwave power levels, but not to the same extent as reported for the AECR. This has motivated us to explore a wide range of second frequencies as well as to experiment with magnetic field configurations and microwave power levels for optimization.

The minimum-B magnetic field configuration, formed by a superposition of an axial mirror field, one with a central minimum, and a radial hexapole field, whose zero coincides with the axis of the source, is a critical component of the ECR2 to confine the plasma and to provide the resonant electron heating. The field increases in all directions away from the center of the source. If two microwaves at different frequencies are launched into the source, the magnetic field configuration needs to be adjusted to produce two well-separated ECR surfaces within the minimum-B field and a quiescent plasma condition can be created to allow high charge states to develop. Consequently, it is important to experimentally determine the strength of the minimum field, B_{MIN}, relative to the resonance field, B_{ECR}, expressed as $B_{ECR} = f_{ECR}/28$ where B_{ECR} is in Tesla and f_{ECR} is the microwave frequency in GHz.

Prior to measurements of B_{MIN} with only the TWTA transmitter in operation, the POISSON design model was used to simulate the axial mirror fields of ECR2 for different coils settings. Table 1 shows calculated results for fields at the injection (B_{INJ}), center (B_{MIN}), and extraction (B_{EXT}) of the plasma chamber as well as microwave frequency calculated for the condition of the absolute minimum confinement defined by the ratio of B_{MIN} to B_{ECR} to be equal to unity. These calculated results determined the TWTA frequency range to be varied between 8.5 and 10 GHz for measurements.

TABLE 1. Axial magnetic fields at the injection (B_{INJ}), center (B_{MIN}), and extraction (B_{EXT}) of the plasma chamber as calculated with the POISSON code. In the calculations two middle coils are varied from 250 A to 500 A in increments of 50 A, while the outermost six coils are held at 500 A.

Six Coils at 500 A				
Two Mid Coils [A]	B_{INJ} [T]	B_{MIN} [T]	B_{EXT} [T]	f_{ECR} at B_{MIN} [GHz]
500	1.8360	0.3551	0.9005	9.94
450	1.8197	0.3397	0.8865	9.51
400	1.8032	0.3243	0.8724	9.08
350	1.7866	0.3089	0.8583	8.65
300	1.7698	0.2935	0.8442	8.22
250	1.7528	0.2780	0.8300	7.78

We tested these calculated results experimentally by varying the TWTA frequencies at low microwave powers and/or by adjusting the two middle coils until a small plasma was ignited. Currently analysis is in progress to evaluate how good the agreement is between the measured and calculated B_{MIN}. If the results turn out to be consistent, then the axial mirror fields simulated with the POISSON code can serve as a guide to find the optimum operating frequencies of the TWTA for the two-frequency heating technique.

[1] Z.Q. Xie and C.M. Lyneis, Rev. Sci. Instrum. **66**, 4218 (1995).