Upgrading the ECR2 magnetic field profile

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In 1996 the ECR2 ion source was originally constructed with the discarded copper plasma chamber containing the original samarium-cobalt permanent-magnet hexapole from ECR1. When the ECR2 ion source was upgraded from a 6.4 GHz ECRIS used exclusively for beams of light elements such as lithium to then operate at 14.5 GHz microwave injection, the upgrade was modelled after some features of the successful AECR-U ion source at LBL but retained features of the 6.4 GHz source, e. g. much larger volume than AECR-U and the existing copper axial coils. A new aluminum plasma chamber with NdFeB permanent magnets and a steel injection plug with large slots appropriate for injection of both 14.5 GHz and 6.4 GHz microwave injection were constructed, and higher-power coil power supplies were purchased. One plan was that 6.4 GHz could be used in addition to 14.5 GHz for two-frequency operation. This idea of added 6.4 GHz injection was not successful, and ECR2 has not shown the performance of AECR-U. A study has been made of upgrade possibilities, and some of these have been implemented.

Upgrading the 14 GHz ECR2 ion source necessarily involves increasing the magnetic fields that contain the plasma. It has been shown by experiments with superconducting ECR ion sources that certain fields are optimum in obtaining plasma containment and stability along with the best performance. At the injection end of the source the magnetic field at the position of the biased plate should ideally be at least three times the resonance field, and according to some results intensities of high charge states continue to go up as this factor increases to 4.5. (For the state-of-the-art 18 GHz sources this factor is 3.9.) The pole strength of the hexapole at the radius of the plasma chamber should be approximately double that of the resonance field. The field at the plasma electrode at extraction should be slightly less than the hexapole strength, but somewhat variable depending on whether the extraction of the highest charge-states or the highest intensity of medium charge-states is desirable. The opinion on what the minimum field at the center of the plasma should be varies. BMIN equal to 75% of BECR has been quoted, but many sources function below this, and high BMIN leads to high x-ray flux. For 14.5 GHz, BECR = 0.517 T, so BINJ ≈ 2.0 T, BRAD (wall) ≈ 1.0 T and BMIN ≈ 0.39 T should lead to the best performance.

POISSON calculations showed how BINJ for ECR2 could be substantially raised with a steel injection plug with smaller slots and with a steel internal biased disk. The slots in the original ECR2 steel plug were modelled with stacking factors included along the outer radii. This may not be entirely accurate, but it does result in lowering the calculated injection field of the original plug by almost 0.2 T. Table 1 compares the fields reported for AECR-U with the calculated fields for the original plug and with the present calculated fields for ECR2. This table mainly shows that BINJ for ECR2 has been raised by about 45% into a range above that for BINJ for AECR-U.

Table I. Comparison of the axial magnetic fields of AECR-U and ECR2.

	AECR-U (1997)	ECR2 500 A (2002)	ECR2 w/steel 0.19" biased disc	ECR2 w/ Steel biased disc and new plug
B_{INJ} max (typical)	1.7 T (1.5 T)	1.28 T	1.59 T	1.85 T
B_{MIN} max	0.4 T	0.35 T	0.353 T	0.356 T
B_{EXT} max (typical)	1.0 T (0.9 T)	0.90 T	0.90 T	0.90 T

The effect of increasing BINJ has not been definitively measured due to pressure to use the source for K150 operation. However, some results have been encouraging. In cyclotron operation, the beam has seemed to be more stable, and in the observation of very low-intensity, high-charge-state ions extracted from the cyclotron, higher charge-states have been enhanced specifically for silver, xenon, and zirconium [1].

With new permanent magnets, the ECR2 hexapole can have larger magnetic fields at the position of the flutes, which lie along the poles of the hexapole, at the expense of smaller fields between the poles. Table 2 gives some fields as reported by LBNL for the 14 GHz AECR-U [2] and as calculated here for ECR2 with PANDIRA. The BRAD at the wall for ECR2 was calculated using the BR and HC measured by the vendor for the NdFeB magnets, UGIMAG. The geometry was somewhat simplified in that the grooves along the sides of the magnets were not included. A measurement of 0.757 T average at the wall was reported when the hex was first assembled here, in good agreement with the calculation when the addition of the grooves and the thickness of the Hall probe are considered.

Table II. Comparison of the hexapolar magnetic fields at the plasma-chamber wall on the poles for AECR-U and ECR2.

	AECR-U	ECR2 original
B_{RAD} (wall)	0.85 T	0.79 T

The AECR-U used 14 and 10 GHz (BECR = 0.50 and 0.36 T, respectively) when these fields were reported. The reported running fields were BINJ = 15 T and BEXT = 0.9 T.

The magnetic axes of the blocks in the ECR2 hex are oriented by an angle of 30° to the radial with each side of a bar having magnetic axis oriented 60° with respect to the axis of the other side of the bar. If the same magnetic material would be used as before with axes oriented 50° to the radial (one side 100° from the other in each bar) stronger pole fields would result but also weaker field between the poles. The inner diameter of the ECR2 plasma chamber is 5.124". These calculations use the original BR=13200 and HC= -12500 are summarized in Table III. Somewhat higher grade materials are available today.

Table III. Comparison of the ECR2 hexapolar magnetic fields with different orientations of the magnetic axis of the NdFeB.

	30°, R=2.562"	30°, R=2.50"	50°, R=2.562"	50°, R=2.50"
Pole	0.792 Tesla	0.745 T	0.954 T	0.886 T
Between Poles	0.657 T	0.654 T	0.592 T	0.60 T

The 50° case results in a 17% increase in pole strength. Fairly recently the KVI cyclotron lab increased the magnetic field pole strength for their AECR-U source from 0.72 Tesla to 0.87 Tesla by such a strategy. The angle to the radial of the magnetic axis for the new hex is 60° (Fig. 1). KVI has reported a ten-fold increase in 129Xe33+ and two more observable high-charge-states even though their 14 GHz transmitter was operating at 500 watts for the new results and 800 watts for the old [3}. Privately, KVI has reported that they had eventually doubled the production of 129Xe35+ just before the failure of their transmitter [4].

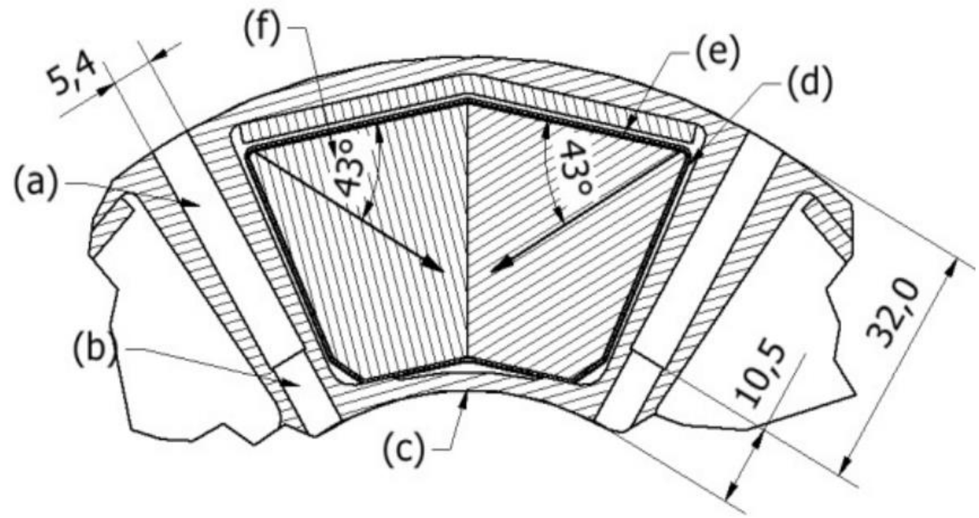

Fig. 1. The KVI permanent-magnet bars. The 43° angle of magnetization measured from the outer face translates into a 60° angle with respect to the radial direction.

The change in angle does affect the forces on the permanent-magnet bars. Using the FORCE application on the PANDIRA files gives a slightly smaller radially inward force of 2 X 21.54 lbs/in (990 lbs for a 23 in long bar) for the 50° case compared with 2 X 24.53 lbs/in (1128 lbs for a 23" bar) for the 30° case . The total radial pressure is 16.1 psi for the 50° case down from 18.3 for the 30° case. The force pushing apart the two halves of a bar, well apart from the other bars, is 56.6 lbs/in (1300 lbs for the 23" bar) for the 50° case as compared to 36.9 lbs/in (850 lbs) for the 30° case. As the six bars are inserted into their slots in the plasma chamber, the azimuthal force builds up to a maximum 141 lbs/in for 50° compared to a maximum of 134 lbs/in for 30°. In short, the radial pressure on the plasma chamber due to the bars decreases by 12% while the azimuthal force on the pinning of the bars increases by 5%. After the bars are seated this azimuthal force is shared by the structure of the plasma chamber.

At present a study is being made of the construction of a new aluminum plasma chamber although the existing plasma chamber is adequate to accommodating new NdFeB bars.

[1] B.T. Roeder *et al., Progress in Research*, Cyclotron Institute, Texas A&M University (2021-2022), p. IV-60.

[2] Z.Q. Xie and C.M. Lyneis. Proceedings of the 13th International Workshop on ECR Ion Sources, College Station, Texas, 1997, p. 16.

[3] H.R. Kremers *et al.*, Proceedings of the 23rd International Workshop on ECR Ion Sources, Catania, Italy, 2018, p. 125
[4] H.R. Kremers, private communication