# Production of high intense Ca-ion beam for RILAC II acceleration

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Calcium(Ca)-48-ion beam is indispensable for studying light nuclei with excess neutrons. The $^{48}$Ca beam was obtained from RILAC as an injector for RIBF accelerators before the upgrade of RILAC with superconducting (SC) acceleration cavities.[1)] The injection line for the RIBF cyclotrons was removed owing to the construction required for the upgrade, and has not been restored at present. Currently, the only way is to use RILAC II, which is mainly used to inject heavy ion beams (krypton, xenon, uranium), as the injector for RIBF. Despite the global shortage of $^{48}$Ca (natural abundance = 0.187%) samples, it is estimated that low-level enriched samples (∼20%) will be available within 2 years. However, the low enrichment of 20% implies that only 20% of the produced Ca beam can be used. Therefore, in accordance with the Ca beam acceleration scheme using RILAC II, we conducted a test to extract ultra-intense $Ca^{11+}$-beam above 100 $\mu$A from a SC-ECR ion source (SC-ECRIS).

The experiment was conducted using an SC-ECRIS for RILAC (R28G-K),[2,3)] which exhibits the same performance as that of RILAC II. An ion-extraction voltage of 13.00 kV was applied to fit to the acceleration scheme. We selected a high-temperature oven (HTO),[4)] which was used in the previous $Ca^{16+}$ beam production last year with good results.[5)] Compared to the previous test, because the $Ca^{11+}$ has a lower charge state, the stable plasma conditions, such as the electron temperature and ion confinement time, differ. The magnetic mirror was set to lower field strength than the $Ca^{16+}$ case, similar to the Ref. 6), resulting in the decreased electron temperature. Natural CaO samples were prepared using the same procedure as in a previous study.[5)] Two evaporation methods to obtain the neutral Ca gas were attempted: direct heating of the sample at temperatures up to 2000°C (DH), and use of the redox reaction of $3CaO + 2Al \rightarrow 3Ca + Al_2O_3$ to lower the Ca evaporation temperature (RR). The DH method is the same method as in the $Ca^{16+}$ beam production, and RR is a common method as presented in Ref. 6). The temperature was controlled by the applied power on the HTO ($P_{\mathrm{HTO}}$). Oxygen ($O_2$) and helium (He) gases were tested as support gases (SGs) to maintain a stable plasma. The total microwave power with frequencies of 18 and 28 GHz, $P_{\mathrm{tot.}}$, as well as the SG flow rate were adjusted to optimize the beam intensity and stability.

Table 1 summarizes the obtained intensities of $^{40}$Ca-ion beam extracted from R28G-K along with the experimental conditions. The data for the ionic charge state $Q = 16$ are obtained from a previous study.[5)] Here, $I_{\mathrm{start}}$ and $I_{\mathrm{stop}}$ represent the beam intensities at the beginning and end of the operation (duration time $\Delta t$), respectively. As shown in Table 1, in all cases of $Ca^{16+}$, the beam intensity gradually increased, and eventually reached to constant values. However, the $Ca^{11+}$ beam intensity tended to decrease with the elapsed time. This trend is more pronounced in the $O_2$ case than in the He case. Note that, in the previous study,[5)] the $Ca^{16+}$ beam intensity was also tested with He support gas; however, it was found to be only half that of the $O_2$ support gas. The DH method seems to cause a chemical reaction between the tungsten crucible and the CaO sample at elevated temperature of ∼2000°C. From the $M/Q$ analyses using the analyzing magnet, when the $P_{\mathrm{HTO}}$ is 700 W, the heavy-ion beams, which appear to be tungsten ions, are not noticeable; however, as the $P_{\mathrm{HTO}}$ is increased to 800 W and 900 W, they become more pronounced. Owing to the chemical reaction, the RR method, which can be used at lower temperature, is preferable to produce low-charge Ca ion beams. Although the measurement time was not sufficiently long, the consumption rate of Ca was estimated to be ∼0.7 mg/h using the RR method using the He gas to produce a $Ca^{11+}$ beam of approximately 100 $\mu$A.

This study has only just begun, and the search for conditions that reduce the Ca consumption is ongoing.

Table 1. $^{40}$Ca ion beam intensities with the charge state $Q$ together with the some experimental conditions such as the support gas (SG) and the Ca evaporation method (Meth.). Measurements were performed over a period of $\Delta t$. See text for other abbreviations.

| $Q$ | SG | Meth. | $P_{\mathrm{tot.}}$ kW | $P_{\mathrm{HTO}}$ W | $\Delta t$ hours | $I_{\mathrm{start}}$ $\mu$A | $I_{\mathrm{stop}}$ $\mu$A |
|---|---|---|---|---|---|---|---|
| 11 | $O_2$ | DH | 3.4 | 900. | 9.3 | 242. | 204. |
| 11 | $O_2$ | DH | 2.7 | 800. | 14.3 | 101. | 59. |
| 11 | $O_2$ | RR | 2.8 | 190. | 17.9 | 74. | 33. |
| 11 | He | RR | 2.1 | 190. | 7.7 | 105. | 90. |
| 16 | $O_2$ | DH | 3.0 | 720. | 16.3 | 84. | 85. |
| 16 | $O_2$ | DH | 3.0 | 660. | 39.7 | 35. | 70. |
| 16 | $O_2$ | DH | 3.0 | 600. | 37.1 | 25. | 30. |

References

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