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**Title**
Development of a radioactive ion beam test stand at LBNL

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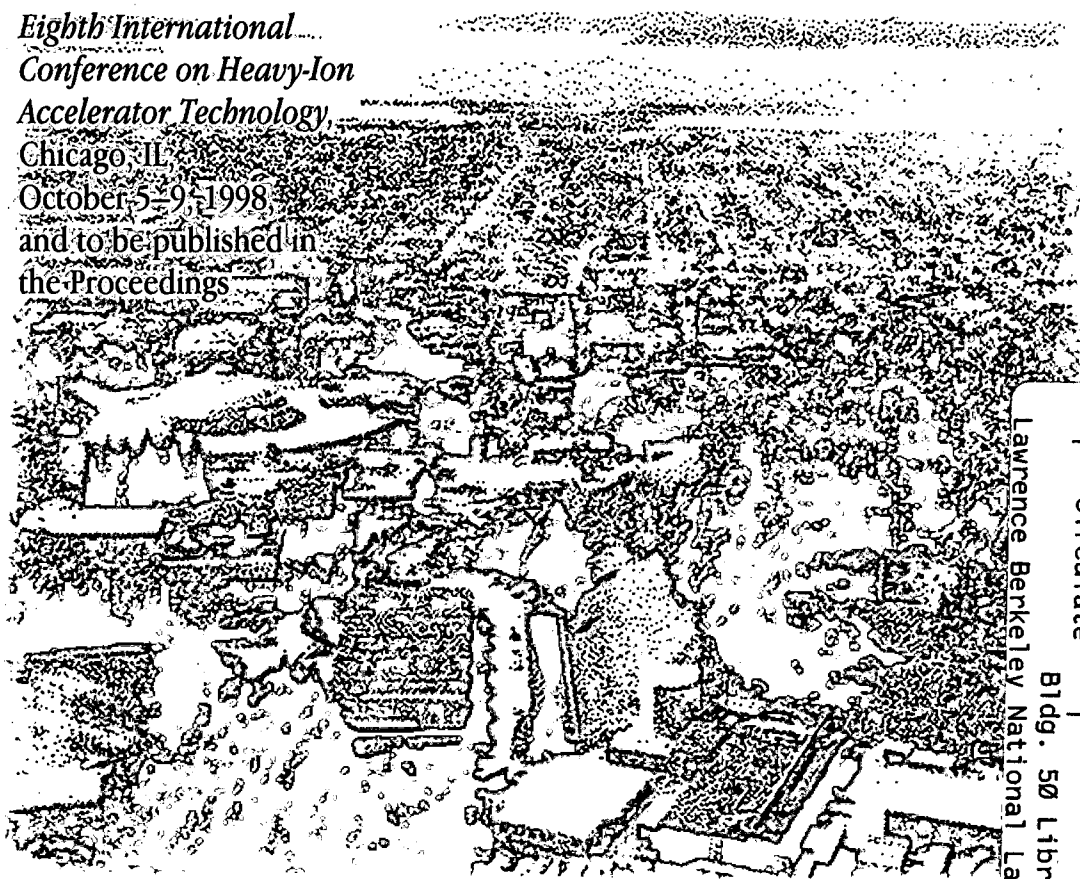# ERNEST ORLANDO LAWRENCE BERKELEY NATIONAL LABORATORY

## Development of a Radioactive Ion Beam Test Stand at LBNL

D. Wutte, J. Burke, B. Fujikawa, P. Vetter,
S.J. Freedman, R.A. Gough, C.M. Lyneis,
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# DISCLAIMER

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# Development of a radioactive ion beam test stand at LBNL

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**Abstract.** For the on-line production of a $^{14}O^+$ ion beam, an integrated target - transfer line ion source system is now under development at LBNL. $^{14}O$ is produced in the form of CO in a high temperature carbon target using a 20 MeV $^3$He beam from the LBNL 88" Cyclotron via the reaction $^{12}C(^3He,n)^{14}O$. The neutral radioactive CO molecules diffuse through an 8 m room temperature stainless steel line from the target chamber into a cusp ion source. The molecules are dissociated, ionized and extracted at energies of 20 to 30 keV and mass separated with a double focusing bending magnet.
The different components of the setup are described. The release and transport efficiency for the CO molecules from the target through the transfer line was measured for various target temperatures. The ion beam transport efficiencies and the off-line ion source efficiencies for Ar, $O_2$ and CO are presented. Ionization efficiencies of 28% for $Ar^+$, 1% for CO, 0.7% for $O^+$, 0.33 for $C^+$ have been measured.

## INTRODUCTION

At the Lawrence Berkeley National Laboratory we have commissioned an ion source test stand for radioactive ion beam development. The primary goal of this test stand is the on-line production of an $^{14}O^+$ ion beam. We are interested in measuring the shape of the decay spectrum for the Gamow-Teller branch in the $^{14}O$ beta-decay (Figure 1) in order to test the conserved vector current hypothesis (CVC) proposed by Feynman and Gell-Mann[1]. The $^{14}O$ half-life of 70 seconds requires producing the isotope on-line at the 88" Cyclotron. $^{14}O$ is generated in the form of CO in a high temperature carbon target using a 20 MeV $^3He^+$ beam from the LBNL 88" Cyclotron via the reaction $^{12}C(^3He,n)^{14}O$.

The $^{14}O$ atoms must be then separated from the other radioactive isotopes produced in the carbon target and implanted into a thin carbon foil in order to:

    (i)     minimize the radiation background
    (ii)    maximize the signal in the beta spectrometer by concentrating the $^{14}O$ sample size.

For this purpose an 8 m stainless steel transfer line connects the target chamber to a cusp ion source [2] through a turbo molecular pumping stage. Thus, the turbo pump separates the target vacuum chamber from the ion source (Figure 2).
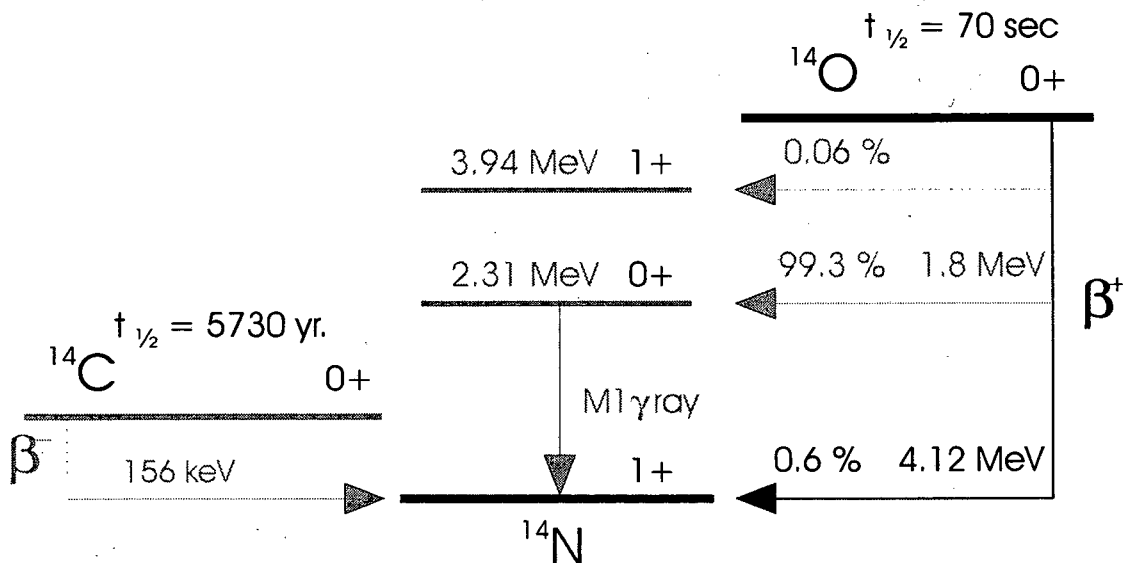
**FIGURE 1.** Mass-14 isospin triplet system.  The transition of interest (4.12 MeV $\beta^+$, $^{14}O \rightarrow {}^{14}N$) is indicated in black

The gas coming from the turbo pump is fed into the ion source and ionized, extracted to energies of 20 to 30 keV and mass separated.  To achieve a small sample size for the beta spectrometer, it is planned to implant the $^{14}O^+$ ions on a 2 mm spot into a thin carbon foil.  This sample will then be transferred to the beta-spectrometer.  At an implantation rate of $2 \cdot 10^7$ pps the required counting time in the spectrometer will be about 150 hours.

The first part of the paper describes the target setup and first experimental results of the high-temperature graphite target.   The second part presents the design and commissioning of the new radioactive ion beam test stand.  The third part discusses the off-line performance of the RF driven multi cusp ion source.

## TARGET SETUP

The half-life of $^{14}O$ is approximately 70 seconds and oxygen is chemically reactive. Given these constraints we decided to develop a high porosity heated solid carbon target. An $^{14}O$ atom produced in the carbon chemically bonds with a carbon atom to form a $^{12}C^{14}O$ molecule.  This molecule has to diffuse to the surface of the local carbon grain and out of the bulk material. The diffusion time of the $^{12}C^{14}O$ out of the target decreases with target temperature.   The molecules then diffuse through 8 m of 5 cm inner diameter stainless steel tubing via molecular flow.  On the other end of the transport line a 220 l/s turbo molecular pump maintains a constant pressure differential between the target chamber and the far end of the transport line.  The output of the turbo molecular pump can be periodically trapped in a small volume, which we then monitor for $^{14}O$ activity.  Two sodium-iodide detectors placed on either side of the sample volume operate in coincidence

to detect the back-to-back 511 keV gamma rays from the beta particle annihilation. A germanium detector is used to detect the 2.3 MeV gamma ray from the $^{14}$O decay simultaneously with the sodium-iodide detectors.

## EXOTIC ION BEAM
## TEST STAND



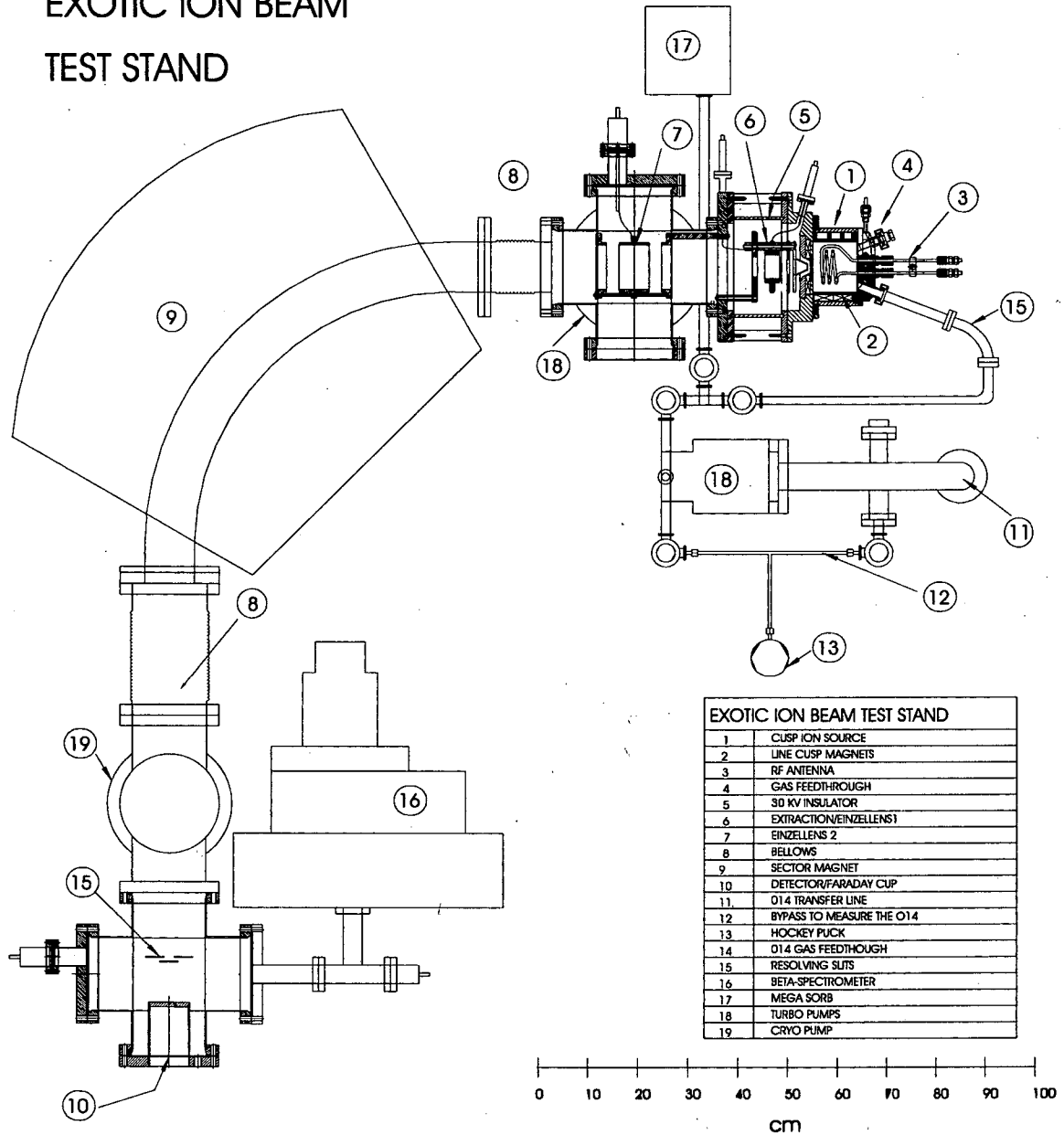| EXOTIC ION BEAM TEST STAND | |
|---|---|
| 1 | CUSP ION SOURCE |
| 2 | LINE CUSP MAGNETS |
| 3 | RF ANTENNA |
| 4 | GAS FEEDTHROUGH |
| 5 | 30 KV INSULATOR |
| 6 | EXTRACTION/EINZELLENS1 |
| 7 | EINZELLENS 2 |
| 8 | BELLOWS |
| 9 | SECTOR MAGNET |
| 10 | DETECTOR/FARADAY CUP |
| 11 | O14 TRANSFER LINE |
| 12 | BYPASS TO MEASURE THE O14 |
| 13 | HOCKEY PUCK |
| 14 | O14 GAS FEEDTHOUGH |
| 15 | RESOLVING SLITS |
| 16 | BETA-SPECTROMETER |
| 17 | MEGA SORB |
| 18 | TURBO PUMPS |
| 19 | CRYO PUMP |

**FIGURE 2.** Setup for the Exotic Ion Beam Test Stand and the O$^{14}$ experiment.

The prototype carbon target was made of carbon felt with a density of 0.082 g/cm$^3$ and an average fiber diameter of a few microns. It was indirectly heated by a tantalum heating filament. With this setup we produced about $2 \cdot 10^6$ atoms of $^{14}$O per second as measured

at the outlet of the turbo molecular pump at a beam current of 5 μA on target and a target temperature of 1500 degrees Celsius. This corresponds to an efficiency of only 0.3 %, of the assumed thick target production rate of $2 \cdot 10^8$pps/μA. We believe that this low number can be attributed to the fact that the hot tantalum surface acts as a getter for CO gas.

Therefore, an all-carbon target was designed with no metals near the heated section of the target. The all carbon target was constructed using reticulated vitreous carbon (RVC, available from ERG Materials and Aerospace). We used the lowest density (0.048 g/cm$^3$) and highest surface to volume ratio. The electrical properties are suitable for direct resistive heating. The target (length of 5 cm, a width of 3.8 cm, and a thickness of 1 cm) has a resistance of 0.20 ohms at 1750 degrees Celsius in a $10^{-5}$ Torr vacuum. Electrical contacts are made by bolting the target to water-cooled electrodes using molybdenum threaded rod. Molybdenum was used because of its high melting point (2600 degrees Celsius). Graphite and boron nitride heat shields were then added concentrically around the target.

With the new target heated to 1720 °C and 2 μA cyclotron beam current on the target, we measured $3 \cdot 10^7$pps of $^{14}$O at the output of the turbo pump. Figure 3 shows the production rate as a function of target temperature. Therefore at 20 μA primary beam current a production rate of $3 \cdot 10^8$pps of $^{14}$O can be expected.

Using the assumed thick target production rate of $2 \cdot 10^8$pps/μA, an efficiency of 7.5 % for the new target has been achieved.
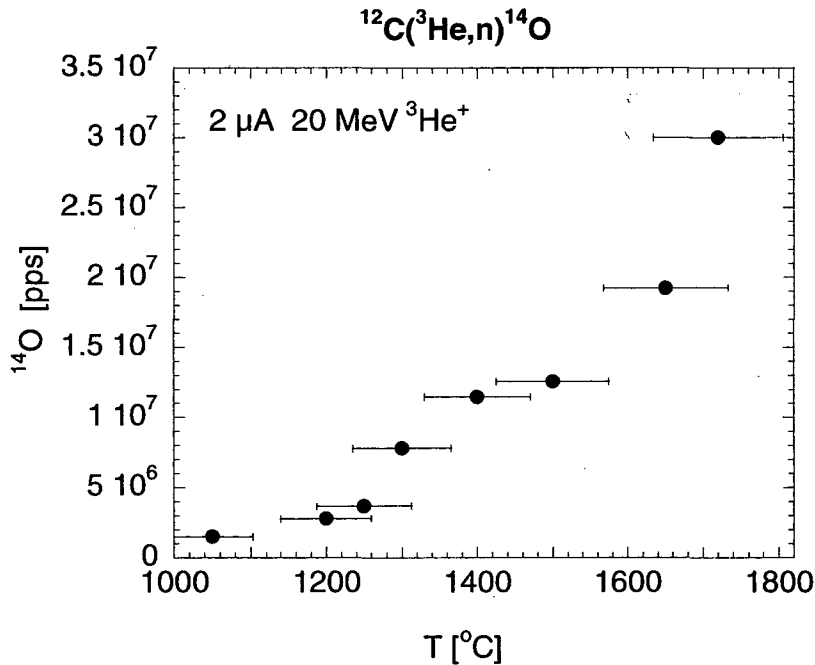


**FIGURE 3.** Production rate as a function of target temperature as measured at the end of the transport line.

# Beam Transport Line

Currently the ion beam test stand consists of a radioactivity transfer line, a multicusp ion source, an accel-decel type extraction system with a 2 mm plasma outlet aperture, two electrostatic einzel lenses, and a mass analyzing magnet.

The ion beam transport line has been designed around an existing double focusing $90°$ sector magnet from the former HILAC injector line at LBNL. It has a bending radius of 54 cm, edge angles of 30 degrees, and a gap width of 3.8 cm. The horizontal waist is located about 43 cm downstream from the vertical waist. Therefore, the ion beam has an elliptical shape after the sector magnet. An additional focusing element will be needed to achieve the required beam spot size of 2mm diameter at the implant foil. The ion source extraction system has been optimized to match the extracted ion beam from the 10 cm RF driven cusp ion source to the acceptance of the analyzing magnet.

The ion beam extraction from a cusp ion source is highly dominated by transverse space charge effects. Since the ion source has to run at a neutral pressure of at least 1 mTorr to sustain the plasma, a high current of ions from the plasma sustaining gas must be unavoidably extracted together with the low current radioactive ion. For instance together with projected $3 \cdot 10^7$ $^{14}O^+$ an additional 1 mA of Argon ions (corresponding to a ion beam density of 30 mA/ $cm^2$) have to be extracted at a relative low extraction voltage of 30 kV (required as implant energy of the $^{14}O$ experiment).

The 30 kV extraction system and the following transport line have been optimized with the ion trajectory code IGUN (3). The use of two einzel lenses allows limited independent control over both beam size and divergence at the magnet entrance. Therefore, the ion optics can be adjusted over a wide range of extraction voltages and current densities (3 mA/$cm^2$ to 60 mA/$cm^2$, corresponding to a total extracted current of 100 e$\mu$A to 2 emA), as verified experimentally. The extraction system and the two einzel lenses are mounted on a single flange to ensure a proper alignment.

Figure 4 shows an IGUN simulation for a 30 keV 1 mA $Ar^+$ beam (30 mA/$cm^2$) through the extraction system and the first einzel lens. Figure 5 shows the continuation of the ion beam through the second einzel lens to the entrance of the sector magnet. Figure 6 demonstrates the rotation of the RR' emittance figure as the ion beam proceeds through the optic system for an 18 keV 0.4 mA and a 30 keV 1 mA $Ar^+$ beam. At the entrance of the magnet the ion beam is slightly divergent and provides a virtual image point about 3 m upstream. The ion beam through the electrostatic einzel lens system was simulated without space charge compensation.
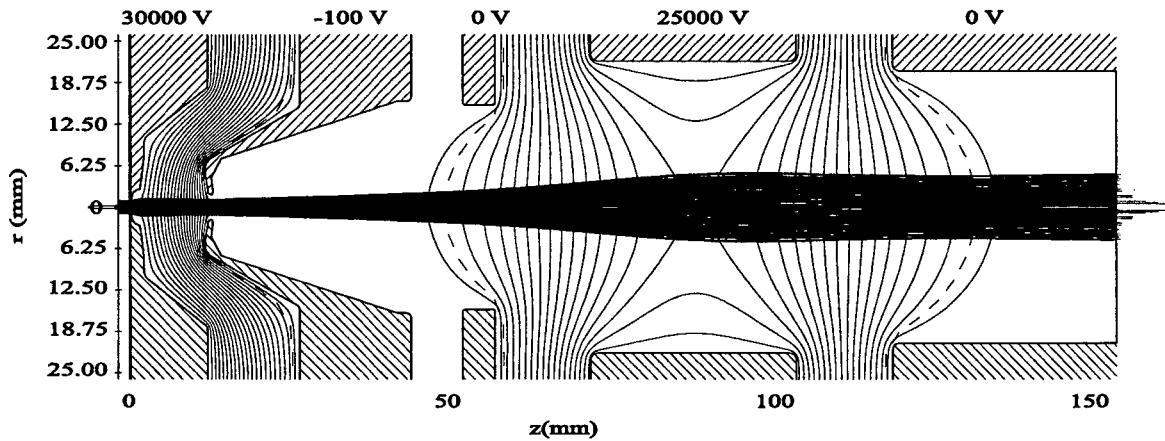
**FIGURE 4.** IGUN simulation run for a 30mA/cm$^2$ (1 mA) Ar$^+$ beam showing an overview of the extraction system including the 1$^{st}$ einzel lens.
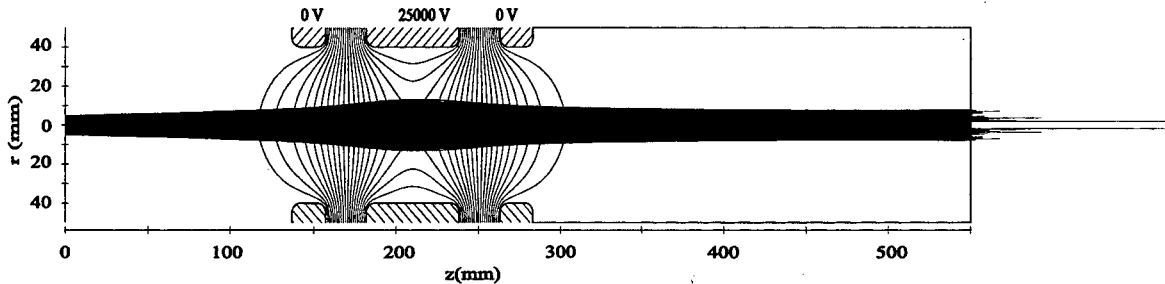


**FIGURE 5.** Continuation of the ion beam trajectories from figure 4 through the second set of einzel lenses to the entrance of the sector magnet.
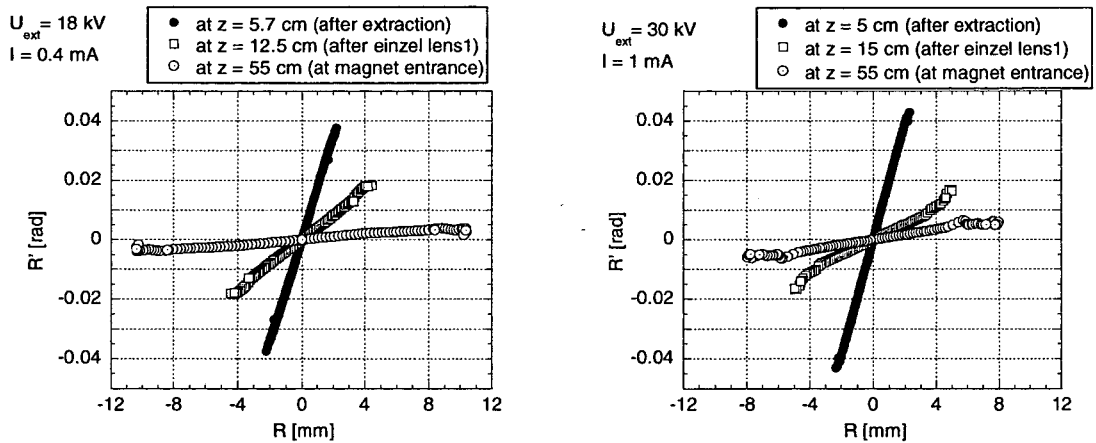


**FIGURE 6.** Change of the RR' emittance as the beam proceeds through the optics system for a 12 mA/cm$^2$ Ar$^+$ beam and a 30 mA/cm$^2$ Ar$^+$.

**TABLE 1.** Predicted beam size and measured transmissions for various ion beam densities and open resolving slits (30 x 30 mm) after the sector magnet.

| current | Argon | | | Oxygen | | |
|---|---|---|---|---|---|---|
| | max. experim. transmission for 30x30 mm resolving slits | TRACE 2D beam ellipse at resolv. slits x[mm] | y[mm] | max. experim. transmission for 30x30 mm resolving slits | TRACE 2D beam ellipse at resolv. slits x[mm] | y[mm] |
| 0 mA | | 10 | 2 | | 9 | 2 |
| 0.15 mA | 95 % | 16 | 8 | | | |
| 0.2 mA | 85 % | 18 | 10 | | | |
| 0.4 mA | 67 % | 27 | 17 | 100 % | 20 | 12 |
| 1 mA | 50 % | 50 | 35 | 82 % | 35 | 25 |
| 1.8 mA | | | | 63 % | 55 | 40 |
| 2.2 mA | | | | 50 % | 60 | 45 |

The beam transport through the analyzing magnet to the Faraday Cup was simulated with the first order matrix code TRACE2D, which includes space charge effects. The output beam parameters of IGUN have been used as input parameters for TRACE2D, providing a full simulation from the plasma meniscus into the Faraday Cup.

We have found a good agreement between the simulated and experimental lens voltages for optimal transmission of the ion beam through the sector magnet. As predicted in the simulations, there are no beam losses in the electrostatic lens system.

The measured ion beam transmission for different plasma parameters for fully opened resolving slits (30 mm x 30 mm) after the sector magnet is summarized in table1. For comparison, the TRACE2D calculated beam spot size at the resolving slits is also listed. Depending on the discharge pressure, the beam line pressure is in the pressure range of $1 \cdot 10^{-7}$ and $7 \cdot 10^{-6}$ Torr. At these low pressures, the degree of space charge neutralization will be small and we have therefore neglected the effect in the calculation.

Experimental ion beam transmissions of 85 %-100 % for the lower ion beam densities and 50-65 % for the higher current densities have been achieved.

# OFF-LINE ION SOURCE TESTING

A detailed description of the RF driven multi cusp ion source used in this study, together with its basic characteristics can be found elsewhere (2) The magnetic plasma confinement is achieved by 14 columns of samarium-cobalt permanent magnets, which form a longitudinal line cusp configuration. The plasma is inductively heated by up to 2kW of RF power (13.56 MHz).

With this type of ion source, the main concern with respect to the production of radioactive ion beams is the minimum discharge pressure required to sustain a plasma, which complicates the beam transport with a high extracted current. The other concern is the lifetime of the rf-antenna, which is reduced due to the continuous bombardment of heavy ions in the plasma (4,5).

Therefore the performance of the cusp ion source has been evaluated off-line with respect to the three major requirements of the planned experiment:

(i)     To achieve the necessary $^{14}$O particle current of 1-2·10$^7$ pps at the implant target, the ion source should be able to provide 10 % ionization efficiency for $^{14}$O$^+$.

(ii)    The gas hold up time in the ion source must be less than one $^{14}$O half-life.

(iii)   At the above mentioned implantation rate of 1-2·10$^7$ pps the expected continuous run of the experiment will be at least 150 hours. Therefore, the ion source should continuously operate at least 200 hours.

Ionization efficiencies were measured off-line for singly charged argon, oxygen, carbon, and carbon monoxide ions with calibrated leaks. The presented efficiencies quote the overall system efficiencies (ion source and transport line). The maximum ionization efficiencies for all measured species are summarized in Table2. The experimental gas hold up time is described by the exponential fit $A \cdot \exp(-t/\tau_{fast}) + B \cdot \exp(-t/\tau_{slow})$. The fast component describes the holdup time of the ions in the plasma, the slow component is related to the wall sticking time. About 70 % of the signal is dropped within $\tau_{fast}$.

A promising ionization efficiency of up to 28% for a calibrated argon leak (leak rate 1.9·10$^{-5}$ scc/sec) has been measured with the RF driven multicusp ion source (see Figure 7). O$_2$ was used as support gas. The maximum ionization efficiency has been achieved at an oxygen discharge pressure of 2 to 3 mTorr. At lower pressure, the RF coupling was less effective, thus resulting in high reflected power and a reduction in the ionization efficiency.

Nevertheless, for CO$^+$ and O$^+$ the ionization efficiencies are much lower than with noble gases. Efficiencies have been measured with a calibrated CO leak (2.3·10$^{-6}$ scc/sec) with argon as support gas for C$^+$, O$^+$ and CO$^+$. With the cusp source the best efficiencies achieved have been 1 % for CO$^+$, 0.7 % for O$^+$ and 0.33 % for C$^+$. In general rather long ion source hold up times have been observed, the longest has been measured for O$^+$.

**TABLE 2.**Ionization efficiencies and hold up times of the RF driven cusp ion source,

| ion | cal. leak | leak rate (scc/sec) | equival. pµA | support | efficiency | holdup time | |
|---|---|---|---|---|---|---|---|
| | | | | | | $\tau_{fast}$ | $\tau_{slow}$ |
| $C^+$ | CO | $2.3 \cdot 10^{-6}$ | 9.5 | Ar | 0.33 % | 13 sec | 86 sec |
| $CO^+$ | CO | $2.3 \cdot 10^{-6}$ | 9.5 | Ar | 1 % | 17 sec | 84 sec |
| $O^+$ | CO | $2.3 \cdot 10^{-6}$ | 9.5 | Ar | 0.7 % | 42 sec | 77 sec |
| $O^+$ | $O_2$ | $2.1 \cdot 10^{-5}$ | 154 | Ar | 0.7 % | 36 sec* | — |
| $O^+$ | $O_2$ | $2.1 \cdot 10^{-5}$ | 154 | He | 0.45 % | 154 sec* | — |
| $Ar^+$ | Ar | $1.9 \cdot 10^{-5}$ | 70 | $O_2$ | 28 % | 6 sec | 32 sec |

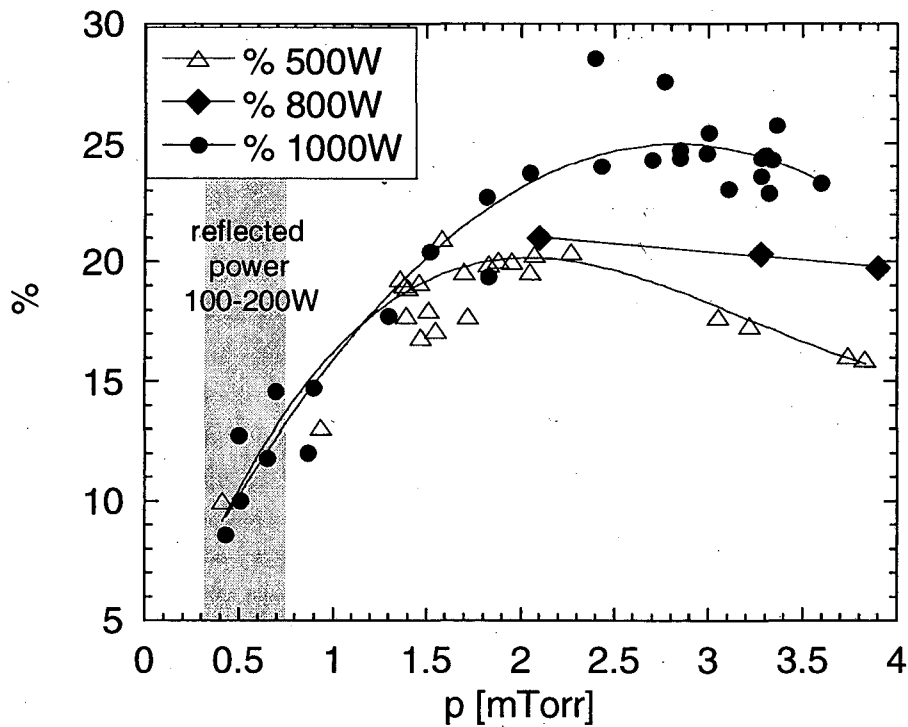*Fast component fitted only.



**FIGURE 7.** Ionization efficiency for $Ar^+$ (100% equivalent to 70µA $Ar^+$) with $O_2$ as support gas for 500W, 800W and 1000W RF input power and various $O_2$ discharge pressures.
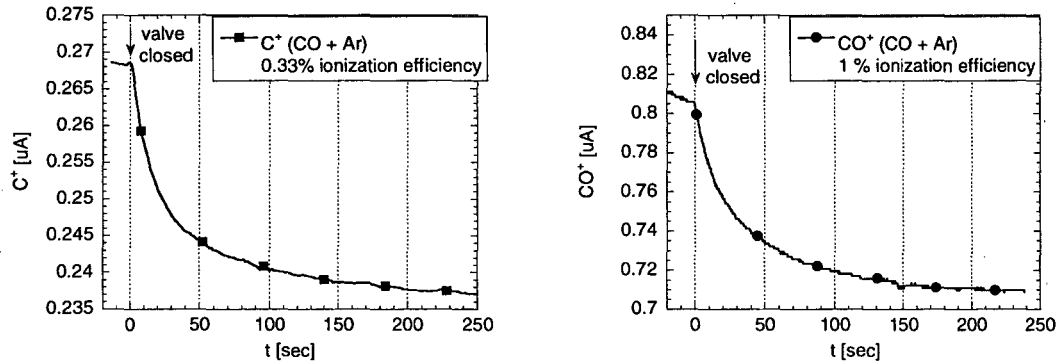
**FIGURE 8.** CO$^+$ and C$^+$ ionization efficiency and hold up time in the cusp.
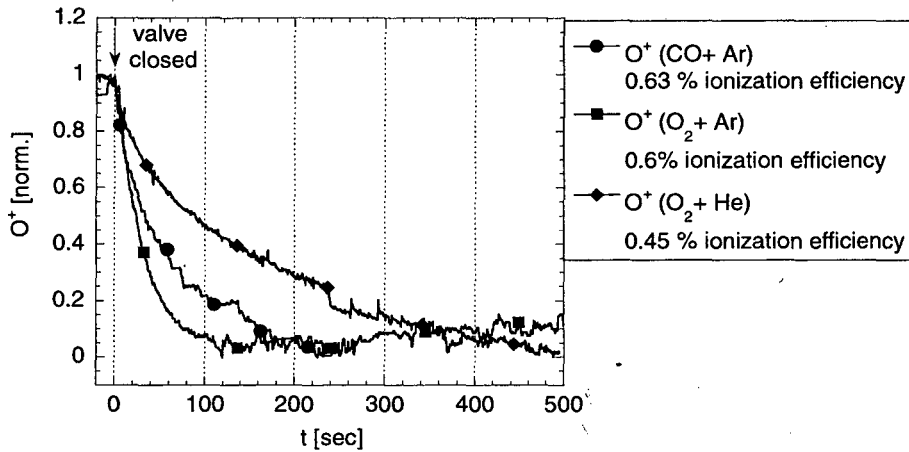


**FIGURE 9**     O$^+$ ionization efficiencies and hold up times in the cusp source for the CO leak (Ar as support gas), the O$_2$ leak (Ar as support gas), and the O$_2$ leak (He as support gas).

With an O$_2$ leak (2.1·10$^{-5}$ scc/sec) argon and helium have been used as support gases to measure the O$^+$ ionization efficiencies. With argon as support gas an ionization efficiency of 0.7 % has been measured and with helium 0.45 %. For He as discharge gas the ion source had to be operated at higher gas pressure to sustain a plasma, thus explaining the lower gas efficiency and longer hold up time.

The hold up times for O$^+$ varied for all three cases (CO leak with Ar, O$_2$ leak with Ar, O$_2$ leak with He). The shortest hold up time was measured with argon as support gas and the O$_2$ leak, the longest with helium and the O$_2$ leak.

The results for the CO and O$_2$ leak are summarized in Figure 8 and Figure 9.

The discrepancy between the argon efficiencies and the carbon or oxygen efficiencies may be explained by the differences in the plasma wall sticking probabilities. Noble gases can be recycled into the plasma, explaining the high efficiency for argon. On the contrary, carbon and oxygen tend to stick at the plasma chamber wall, leading to low source

efficiencies in the cusp ion source. For carbon, this effect was demonstrated by the deposition of a carbon film on the plasma chamber walls. The plasma potential for the RF driven cusp source has been measured to be in the order of 5 V to 10 V. Therefore, the ions can not gain enough energy to sputter the adsorbed atoms and molecules from the plasma chamber walls.

The average ion source lifetime for the above mentioned performance tests was about 15 hours, limited by the failure of the porcelain-coated copper antenna. We believe that the performance of the antenna is limited by micro cracks in the porcelain coating. The RF voltage (in the order of a few 100 V) can penetrate through these cracks and ion sputtering of the coating material becomes the lifetime limitation. This explanation is confirmed by the facts that

i)      copper appears in the ion beam after 6-10 hours of operation, as soon as the antenna begins to fail

ii)     the antenna lifetime is longer for lower masses.

To reduce the sputtering problem, the porcelain-coated antenna was replaced by a quartz antenna. Tin-coated copper threaded wire strands were placed as RF conductors inside a water-cooled quartz tube. The ion source performance of both antenna types was similar. The average lifetime was about 20 h for the quartz antenna, limited by sudden failures of the glass tubes. Since the quartz antenna showed a faint opacity (initially fully transparent), we believe that again plasma sputtering was the lifetime limitation.

## CONCLUSION AND OUTLOOK

A radioactive ion beam test stand has been commissioned with an RF cusp source at the 88" Cyclotron at LBNL. The beam transport line consists of an accel-decel extraction system, two electrostatic einzel lenses, and a double focusing sector magnet. An ion beam transmission of up to 100% has been measured.

A high temperature all-carbon target has been developed. $O^{14}$ intensities of up to $3 \cdot 10^7$ pps have been measured at the entrance to the ion source with $2\mu A$ primary beam intensity from the cyclotron at a target temperature of 1720° C.

The RF cusp source performance has been tested off-line with respect to the $O^{14}$ experimental requirements. The cusp ion source can not fulfill the three major experimental requirements:

(i)     The highest $O^+$ efficiency was only 0.7 %.

(ii)    The gas hold up time in the ion source is in the order of one half-life of $O^{14}$.

(iii)   The average source lifetime with the porcelain-coated antenna is only about 15 hours, and for the quartz antenna about 20 hours.

As a comparison the off-line gas efficiency has been measured on the AECR-U at the 88" Cyclotron for various gases. In Figure 10 the holdup times and measured ionization

efficiencies in the cusp source for $O^+$ are compared with the results for $O^{6+}$ in the AECR-U, which has the highest ionization efficiency of all oxygen charge states. Because the experimental requirement can not be met with the cusp source without further development, and because of the promising results measured on the AECR-U, the cusp ion source will be replaced by a small ECR ion source.
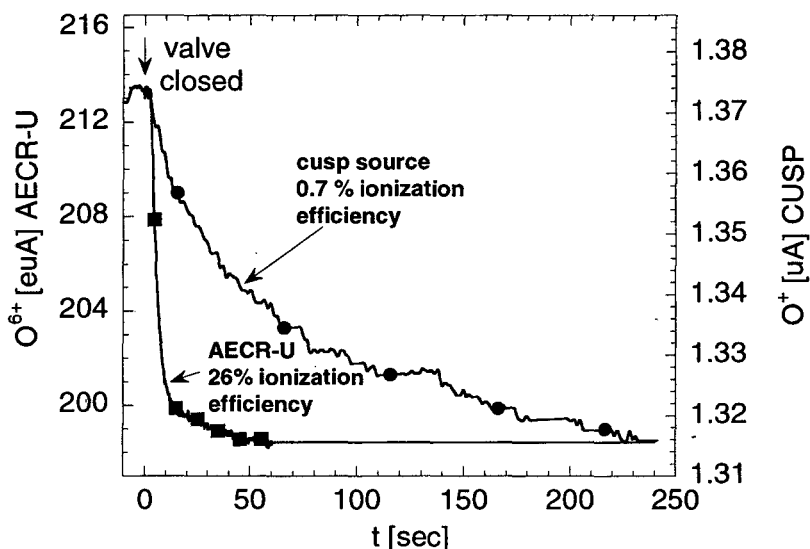


**FIGURE 10.** Comparison of the hold up times for $O^+$(cusp) and for $O^{6+}$ (AECR-U) ion source for a calibrated CO leak. The ion ionization efficiency is indicated in the graph also.

## ACKNOWLEDGEMENT

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