

THE CHARGE-EXCHANGE CELL FOR THE NEUTRAL
LITHIUM BEAM PROBE ON PULSATOR, W7a AND
ASDEX

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(in English)

ABSTRACT

The charge-exchange cell forming a part of the lithium-diagnostic beam-line on Pulsator, Wendelstein 7a and ASDEX is described. The cell consists of a neutralization tube of 12 cm length attached to a reservoir which supplies the neutralizing medium, either lithium or sodium. To reduce cell losses, operation is on a pulsed basis by means of a valve which seals the reservoir during periods when the beam is not on. Using sodium, neutralization efficiencies for a Li^+ beam vary typically from 0.97 % at 20 keV to 57 % at 100 keV.

Introduction

A neutral lithium beam is a useful tool in diagnosing Tokamak plasmas /1/. Implicit in such a diagnostic beam probe is the charge-exchange (cx) cell which is responsible for converting lithium ions into neutrals. This report, essentially intended to be a design and operations manual, presents design criteria for the cx cell employed on Pulsator, W7a and ASDEX, makes estimates of characteristic cell parameters, gives mechanical details, and discusses operational features.

Design Considerations and Consequences

The function of a cx cell is to furnish a localized region of atoms with which beam ions can suffer a cx collision thereby producing neutral beam atoms. As a first approximation, ignoring re-stripping phenomena, the fraction F of a beam which is neutralized after passing through a cx cell is given by

$$F = 1 - \exp(-\bar{n}l \sigma) \quad (1)$$

where σ is the cross section for charge-exchange and

$$\bar{n}l = \int_1 n dl,$$

n being the atom density of the neutralizing media and l the path length through the media. From equation (1) we see that for F to be large, the exponent $\bar{n}l\sigma$ must be of the order one.

σ is largest for resonant or near-resonant charge-exchange; hence a lithium beam favors use of an alkali metal in the cx cell. For reasons of ease in handling, very low vapor pressure at room temperature, and minimum contribution to Z_{eff} of the tokamak plasma, lithium and sodium are the appropriate candidates.

Generally, alkali metals have an advantage over gases in that stick on all unheated surfaces with which contact is made, thereby eliminating the need for extra differential pumping to

maintain a low background pressure in the ion gun. The fact that there was simply not any space for a differential pumping system in the Pulsator beam line (for which the prototype cx cell was constructed) dictated the use of a cx cell operating on an alkali metal basis.

Figure 1 is a schematic of the cx cell type considered here, consisting of a tube of length $2L_1$ through which the beam passes, a reservoir containing either lithium or sodium, and the connection of length L_2 between the neutralizing tube and reservoir. The alkali vapor pressures P_1 and P_2 are established by heating the cell. Given that the pressure falls linearly to zero at the end of the tube ($P_0=0$), then from $\overline{nI} \sigma \gtrsim 1$, we have

$$\frac{n_1}{2} 2L_1 \sigma = n_1 L_1 \sigma \gtrsim 1 \quad (2)$$

where n_1 is the atom density corresponding to P_1 . For resonant charge-exchange σ is of the order 10^{-14} cm^2 , yielding the very general condition

$$n_1 L_1 \gtrsim 10^{14} \text{ cm}^{-2}. \quad (3)$$

There is a trade-off of vapor pressure against cell length: if it is necessary to make the cell short due to a lack of space or to an increasing beam divergence along the beam path, then the vapor pressure must be high. This brings the disadvantage of increased loss of the neutralizing medium to the surroundings.

The loss rate Q may be expressed as

$$Q [\text{Torr-l/s}] = 2 S_{10} P_1 \quad (4)$$

where S_{10} is the pumping speed in l/s from the center to one end of the tube. S_{10} is a function of L_1 and D_1 . On Pulsator, $L_1 = 6 \text{ cm}$ due to space limitations. (In addition to the length restriction, the condition that the cell had to operate in a vertical position precluded the use of commercially available units). Further, D_1 was chosen to be rather large, 2.5 cm,

in consideration of the unknown characteristics of the ion gun still in development in Fontenay-aux-Roses at that time. Therewith, in connection with expression (3), the loss rate is predetermined. Nonetheless, the loss during an operating day can be substantially reduced by making use of the fact that on tokamak experiments the duty cycle of a cx cell is normally less than 1 % (a few seconds every five minutes, for example), i.e. the cell may be pulsed. Here this is achieved by means of a valve which seals the reservoir from the tube during periods when the beam is not on.

The possibility that the seal is not always perfect leads to another design criterium: the pressure P_2 should be low to minimize leakage during the closed phase. We may write

$$Q = (P_2 - P_1) S_{21},$$

or

$$P_2 = P_1 + \frac{Q}{S_{21}} = P_1 \left(1 + 2 \frac{S_{10}}{S_{21}} \right) \quad (5)$$

where S_{21} is the pumping speed of the unsealed connecting tube between the reservoir and the neutralizing tube. P_1 is fixed from expression (3), hence if P_2 is to be kept low, then S_{21} must be maximized, i.e. the connecting tube should be short and have a large bore. In addition, the surface area of the reservoir from which evaporation occurs must be such that the evaporation rate W for the vapor pressure P_2 determined from equation (5) is much larger than the loss rate Q . This assures that P_2 does not significantly increase when the valve is shut; or in other words, that P_2 is an equilibrium vapor pressure.

To be able to roughly quantify the loss rate we assume that both lithium and sodium in the vapor state may be treated as ideal gases. In the molecular flow regime the pumping speeds S_{10} and S_{21} are then given by /2/

$$S_{10} [l/s] = \left(\frac{\pi D_1^2}{4} \frac{\bar{V}}{4} \right) \left(\frac{4}{3} \frac{D_1}{L_1} \right) 10^{-3} \quad (6a)$$

$$S_{21} [1/s] = \frac{\frac{\pi D_2^2}{4} \frac{\bar{V}}{4}}{1 + \frac{3}{4} \frac{L_2 + D_1/2}{D_2}} \times 10^{-3} \quad (6b)$$

$$\text{where } \frac{\bar{V}}{4} [cm/s] = 3.64 \times 10^3 \left(\frac{T [^\circ K]}{M [amu]} \right)^{1/2} \quad (6c)$$

Notice that S is proportional to D^3 , illustrating the advantage of a small tube diameter with respect to reducing loss rates. For our case, with $D_1 = D_2 = 2.5$ cm, $L_1 = 6$ cm and $L_2 = 2.7$ cm, we have

$$S_{10} = 9.9 \left(\frac{T}{M} \right)^{1/2} 1/s \quad (7a)$$

$$S_{21} = 8.2 \left(\frac{T}{M} \right)^{1/2} 1/s \quad (7b)$$

Using equation (5) we see immediately that $P_2 = 3.4 P_1$.

It remains to determine the required cell pressure P_1 . Since high charge-exchange efficiencies are attainable (see Fig.5), the condition $n_1 L_1 \sigma \gtrsim 1$ is more properly replaced by $n_1 L_1 \sigma = 2$. Furthermore, σ may be taken to be about $5 \times 10^{-15} \text{ cm}^2$ /3/, so that $n_1 L_1 \sim 4 \times 10^{14} \text{ cm}^{-2}$ and $n_1 \sim 6.7 \times 10^{13} \text{ cm}^{-3}$. From the ideal gas law it follows that

$$n_1 [\text{cm}^{-3}] = 5.8 \times 10^{17} \frac{P_1}{\sqrt{T}}$$

or

$$T [^\circ K] = 7.6 \times 10^7 P_1^2 [\text{Torr}]. \quad (8)$$

Using $P_2 = 3.4 P_1$, equation (8), and the relationships /4/ between equilibrium vapor pressure and temperature given in Table I, one can solve for P_1 , P_2 and the required reservoir temperature. These values are listed in Table I together with the corresponding pumping speed S_{10} (from equation (7a)) and associated loss rate Q (from equation (4)). Finally, for comparison with Q , the evaporation rate W for the reservoir of surface area 32 cm^2 ($D_r = 6.4$ cm) is given. We note that $W \gg Q$, as desired.

It must be borne in mind that these numbers can be regarded only as estimates. The condition $n_1 L_1 \sigma = 2$ stems from equation (1), which, however, furnishes an incomplete description of the various interactions taking place in a charge-exchange cell. Moreover, σ is known only within experimental error, and the effective value of L_1 is probably greater than the physical value since P_0 will not be exactly zero at the tube end. The assumption that lithium and sodium are ideal gases is probably also suspect. Nevertheless, certain valid conclusions may be drawn: a cx cell operating with lithium must run at a temperature considerably in excess of that required for sodium. In this example the temperature difference is 228°C . This represents a practical disadvantage of lithium: a) the heater windings must carry more current, thereby increasing the chances of a heater failure, and b) the higher temperature causes a higher outgassing rate for the cell and its surroundings, which can imply a longer "bake-out" time to reach a good vacuum after the cell has been exposed to air.

The calculated loss rate Q may be used to gain a feeling for the rate at which cx cell atoms find access to the tokamak plasma. Assuming that the atomic flux from the ends of the cell varies as the cosine of the angle away from the beam line, then the flux at a distance R from one end of the cell is

$$\phi \text{ [atoms/cm}^2\text{-s]} = \frac{Q}{2\pi R^2} \cos \theta. \quad (9)$$

Being specific, the rate ϕ at which atoms enter ASDEX, for example, is limited by an aperture of 1.5 cm diameter at a distance of 72 cm from the cx cell end. Thus, since $\theta = 0$ along the beam line,

$$\phi \text{ [atoms/s]} = \pi \left(\frac{1.5}{2}\right)^2 \frac{Q}{2\pi (72)^2} = 5.4 \times 10^{-5} Q. \quad (10)$$

The corresponding numbers for ϕ are to be found in Table I. To place matters in perspective, a 1 mA Li^0 beam (a typical value

for the ASDEX beam probe) introduces 6.2×10^{15} atoms/s to the plasma, a number much larger than Φ for either lithium or sodium, even when compared in terms of electrons/s for the case of sodium. In other words, the lithium beam, not the cx cell, principally determines the number of alkali metal atoms deposited within the ASDEX vessel.

Mechanical Features

Figure 3 is a simplified drawing showing details of important features of the charge-exchange cell. Photographs of the cell, in a partially open state, from two different viewpoints comprise Figure 4. The flaps attached to the valve rod are for precautionary purposes. They serve to block alkali metal vapor - arising from an imperfectly sealing valve - from streaming directly into the ion source or beam line during periods when the valve is closed.

As already stated, the neutralizing tube length of 12 cm and inner diameter of 2.5 cm are a consequence of limitations originally imposed by Pulsator. The distance from the cell to the flange of about 14 cm also stems from the layout on Pulsator. In view of the success of the initial unit, and continuing spatial restrictions on ASDEX, these dimensions have been maintained for subsequent versions of the cell. The tube connecting the cell to the flange has a wall thickness of only 0.15 cm in order to limit conductive heat loss to the flange.

The flange is made of ARMC0 iron (plated with nickel to prevent rust) as it forms part of the magnetic shielding of the beam line on ASDEX. The valve rod guide material is bronze in order to facilitate smooth gliding of the rod. All other parts are of stainless steel. The valve rod as well as the valve itself is chrome-plated to provide a harder surface.

Before plating, the valve and valve seat are matched by grinding. In the finished unit the quality of the seal is tested (in air) by filling the reservoir with water, heating and then checking

for signs of escaping steam while the valve is closed. In addition, if the reservoir can be heated to substantially more than 100°C (say, 130°C) with the result that the contents explosively escape upon opening the valve, then the seal is judged to be acceptable.

The valve is activated by a pneumatic cylinder operating at about five Bar (in-house pressure). A soft closing is realized by means of an air cushion in the cylinder which becomes effective during the last few millimeters of travel. The suspension of the cylinder and the connection to the valve rod are such as to minimize binding of the rod with the guide.

The reservoir and neutralizing tube are heated by two sets of Philips coaxial heating cable (Type ZEZ AC 10 with cold ends) of length 1.9 m and 4.36 m respectively. A double spiral round groove (width $1^{+0.05}$ mm, depth 0.9 mm) with a pitch of 0.5 cm takes up the heating cable. (For simplicity only one groove is indicated in the drawing of Figure 3). The cable is pressed into and held in the grooves by sleeves (see Figure 4). The sleeves are perforated to promote outgassing in a vacuum.

The power supplies for the heating cables are two Variacs, these having the desirable property that they are innately "hardened" against negative side effects resulting from an arc-down in the ion source.

Thermocouples are brought onto the reservoir and neutralizing tube to monitor temperature. However, since the thermocouple reference temperature next to the flange is unknown, the temperatures registered are lower than those actually prevailing and hence have value only in a relative sense. This is not a serious drawback for practical operation as the measured power input, not the temperature, is used to adjust the cell's charge-exchange efficiency.

Operating Characteristics

In early work with the cx cell where the Li^0 beam energy was low (<25 keV), lithium was used as the charge-exchange medium with good success. However, as the beam energy was increased it became necessary to heat the cell to ever higher temperatures to obtain a good charge-exchange efficiency. Our experience is that at 100 keV a lithium-driven cell uses about 360 watts (value for original version of cell) compared to 75 watts (value for improved cell) with sodium. In addition to the inherent drawbacks associated with the higher temperatures required for lithium, in the energy range of interest (20 - 100 keV) the cross section for charge-exchange of Li^+ on sodium is greater (10 % or more) than that for Li^+ on lithium /3/. These factors have led to the sole use of sodium.

The cell is loaded by cutting away the outer layers of the sodium chunks, thereby revealing the shiny fresh metal, and then pushing the pieces into the cell until they fall into the reservoir. If this is done quickly (say, <10 min.) then there is no need to perform the operation under the protection of an inert gas. The cell is cleaned by cautiously washing with water. Sodium, being more reactive, requires that water be added very slowly.

Typically only a few grams of sodium are introduced to the cell per loading. According to the example summarized in Table I, two grams of sodium would be lost after 8000 seconds of operation, or in other words, after 2000 shots of length four seconds each - a characteristic pulse length time. (The valve is opened a few seconds before turning on the beam voltage so as to allow the sodium pressure to stabilize, and to pump away impurity vapors which were trapped in the reservoir). A serious test involving placing a precise quantity of sodium in the cell and then measuring the elapsed time for complete exhaustion in a closed or open condition has never been carried out. The practical experience that a single loading will last well over a thousand shots, stretching over a period of months of

daily operation, tends to lend credibility to the feeling that such numbers as implied by Table I are not far from the truth. An uncertainty in interpretation on the positive side lies in the fact that during the lifetime of a loading the vacuum is normally broken several times - to renew the emitter in the ion gun, for example. Each time the load has a chance to react with air. Since the surface area offered by the reservoir is large, even a limited interaction can poison a non-negligible fraction of the alkali metal.

In operation, the neutralizing tube cable serves to heat the mass of the cell, the reservoir heater being used to actually fine-tune the vapor pressure. Thereby, the tube is kept some tens of degrees hotter than the reservoir so as to hinder "condensation" in the tube, i.e. so as to guarantee that indeed the reservoir temperature determines the vapor pressure. For instance, for the upper curve of Figure 5 the measured temperatures are 275 and 221°C respectively. As already mentioned, these are relative values. In addition, it must be pointed out that the tube temperature is measured at the hottest point. The reservoir temperature of 221°C is substantially less than the 289°C listed in Table I. Aside from the relative temperature effect, part of the difference might be accountable to the positioning of the thermocouple, or the estimate of 289°C may simply be too high.

With respect to testing of the cell, the beam, after having passed through the neutralization tube, consists of a mixture of neutrals (equivalent current I_b^0) and ions (current I_b^+). If the beam detector is laid out to register the secondary electron current produced by impinging ions and neutrals, as well as the ion current, then the detector current arising from the neutrals is γI_b^0 and that from the ions is $I_b^+(1 + \gamma)$. Here, the secondary electron emission coefficient γ is taken to be equal for ions and neutrals, a reasonable approximation for the beam energies concerned.

γ , a function of the detector geometry, material and prehistory is derived by comparing the ion current, measured with the detector in a Faraday cup configuration, to the corresponding secondary electron current, all for the case of a pure ($I_b^0=0$) ion beam. For the detector used (Molybdenum target) γ was determined to be roughly in the range 2-4, the larger values being associated with higher beam energies.

The efficacy of the cell may be evaluated in terms of the apparent neutralization efficiency ϵ' , a quantity experimentally readily accessible, which is defined as the ratio of the detector current due to beam neutrals ($I_d^0 = \gamma I_b^0$), to the detector current arising from the total beam ($I_d = \gamma(I_b^0 + I_b^+) + I_b^+$).

$$\epsilon' = \frac{I_d^0}{I_d} = \frac{\gamma I_b^0}{\gamma(I_b^0 + I_b^+) + I_b^+} \quad (11)$$

I_d^0 is that current measured when all ions are magnetically deflected from the beam before they reach the detector. Thus I_d^0 and I_d represent the detector signals with and without activation of the deflection magnet.

Figure 5 illustrates the relationship between ϵ' and beam energy E_b for reservoir input powers P_{res} of 4, 9 and 15.8 watts at a tube power of 59 watts. The setting of 15.8 watts is appropriate for moderate to high beam energies. ϵ' can be increased still further for all energies by raising P_{res} . However, depending on the beam energy the benefit can be marginal: For example, we see in Fig. 6, where ϵ' is plotted against P_{res} for $E_b = 20, 60$ and 100 keV, that for 20 keV ϵ' has only a weak dependence on P_{res} for $P_{res} \gtrsim 12$ watts. That is to say, at 20 keV there is apparently little to be gained by increasing P_{res} beyond this value. Moreover, beyond 12 watts the very modest change in ϵ' (for 20 keV) must be weighed against the augmented cell losses (the vapor pressure of sodium goes up by more than 50 % for a 10°C change in reservoir temperature - see Fig. 2). Figure 6 makes clear that this point of "marginal return" increases with beam energy, i.e. higher beam energies require higher reservoir powers.

The actual physical quantity of interest, the neutralization efficiency ϵ , is related to ϵ' via

$$\epsilon = \frac{I_b^0}{I_b^0 + I_b} = \left(\frac{1 + \gamma}{\epsilon' + \gamma} \right) \epsilon' \quad (12)$$

from which it is apparent that $\epsilon > \epsilon'$ since $\epsilon' < 1$. In Figure 5 ϵ' ranges from 0.95 at 20 keV to 0.51 at 100 keV. The corresponding values of ϵ (with $\gamma = 2,4$ at $E_b = 20, 100$ keV) are 0.97 and 0.57, i.e. only somewhat larger than ϵ' . In view of the uncertainties in ϵ' and γ , no graph of ϵ is presented.

Finally, it should be stated that use of the cx cell did not lead to a detectable increase in the half-width of the lithium beam. If anything, the beam is somewhat better collimated when the cell is activated.

Summary

A charge-exchange cell operating with either lithium or sodium has been developed for the IPP neutral lithium beam probe. The cell consists of a neutralization tube, of length 12 cm and inner diameter 2.5 cm, attached to a reservoir which supplies the neutralizing medium, either lithium or sodium. To reduce the loss of neutralizing medium operation is on a pulsed basis by means of a valve which seals the reservoir during periods when the beam is not on. Practical experience indicates that the seal is effective and that the estimated loss rate for sodium of $\sim 2.5 \times 10^{-4}$ g/s for the valve-open case is of the correct order of magnitude. Neutralization efficiencies approaching 60 % for $E_b = 100$ keV are achieved without degradation of other beam qualities.

Acknowledgements

Special thanks are due to Mr. K. Sahner who built the first charge-exchange cell from incomplete, primitive sketches, and to Mr. H. Schmid who was responsible for the improved versions used on W7a and ASDEX. I thank Miss H. Sittig for drawing the figures contained in this report.

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TABLE I

ELEMENT	Li	Na
Vapor Pressure /4/		
log P [Torr]	$7.5 - \frac{7480}{T[^\circ\text{K}]}$	$7.71 - \frac{5480}{T}$
Evaporation Rate /4/		
log w [g/s]	$6.6867 - \frac{7480}{T} - 0.5 \log T$	$7.1568 - \frac{5480}{T} - 0.5 \log T$
P_1 [Torr]	3.2×10^{-3}	2.7×10^{-3}
P_2 [Torr]	1.07×10^{-2}	9×10^{-3}
T [°K]	790	562
S_{10} [l/s]	105	49
Q [Torr-l/s]	0.67	0.26
[atoms/s]	1.4×10^{19}	6.5×10^{18}
[g/s]	1.6×10^{-4}	2.5×10^{-4}
W [g/s]	1.9×10^{-3}	3.5×10^{-3}
Φ [atoms/s]	7.6×10^{14}	3.5×10^{14}
[electrons/s]	2.3×10^{15}	3.9×10^{15}

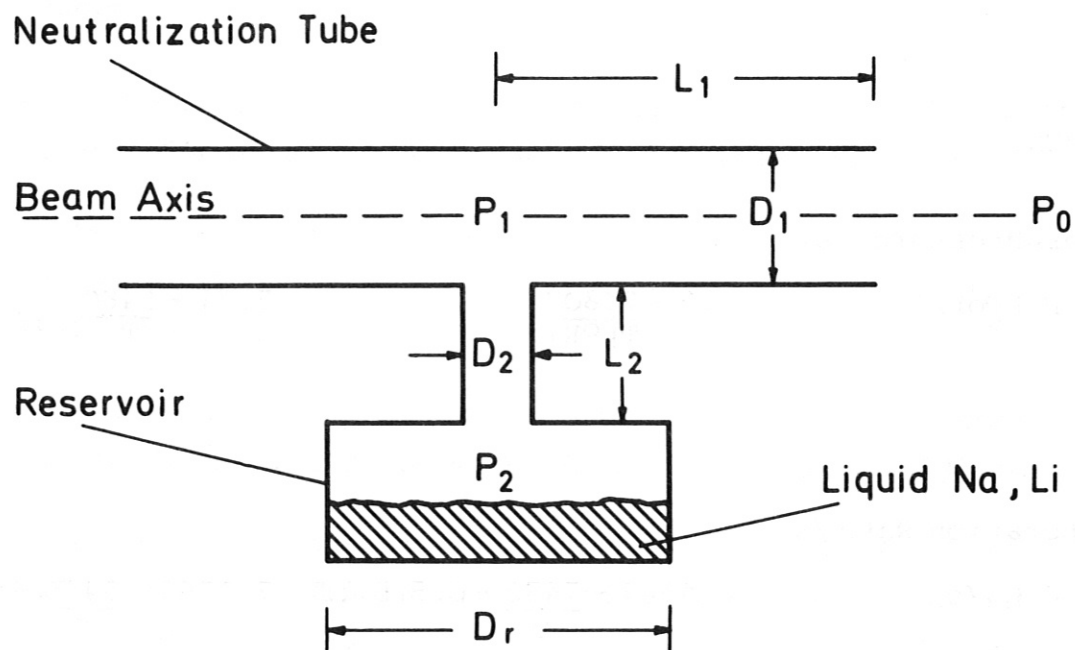


Fig.1 Schematic of a Charge-Exchange Cell

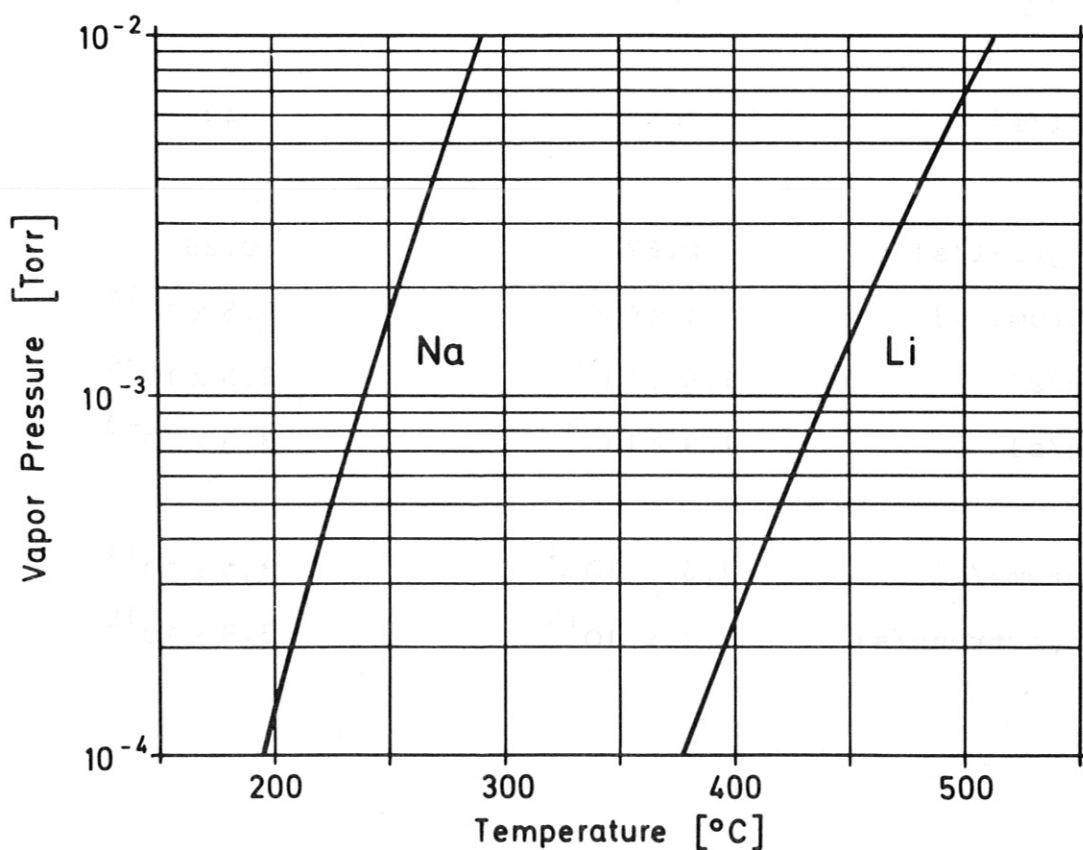


Fig.2 Equilibrium vapor pressure of Li and Na vs. temperature

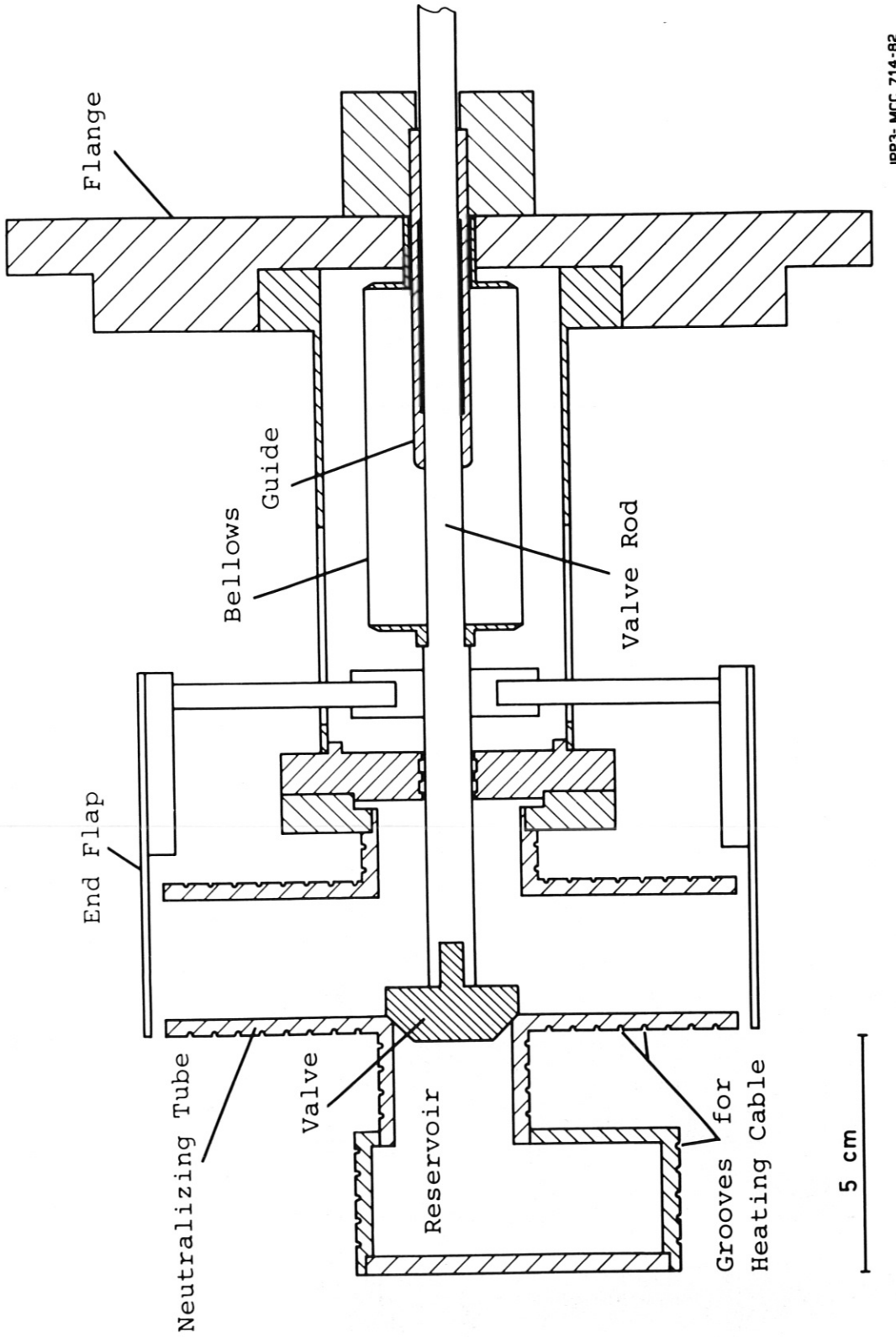


Fig.3 Simplified drawing of the ASDEX charge-exchange cell

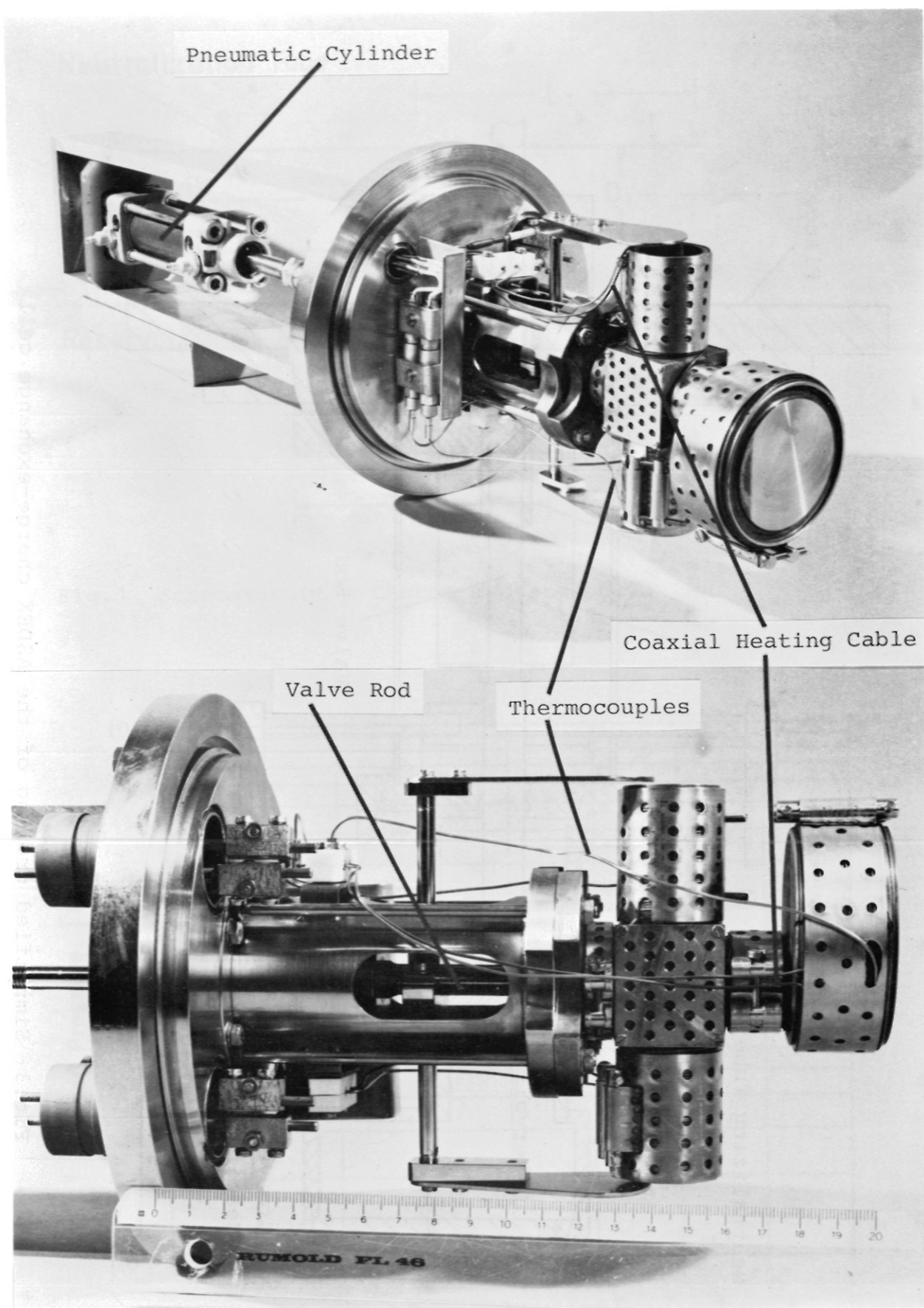


Fig.4 Photographs of the ASDEX charge-exchange cell

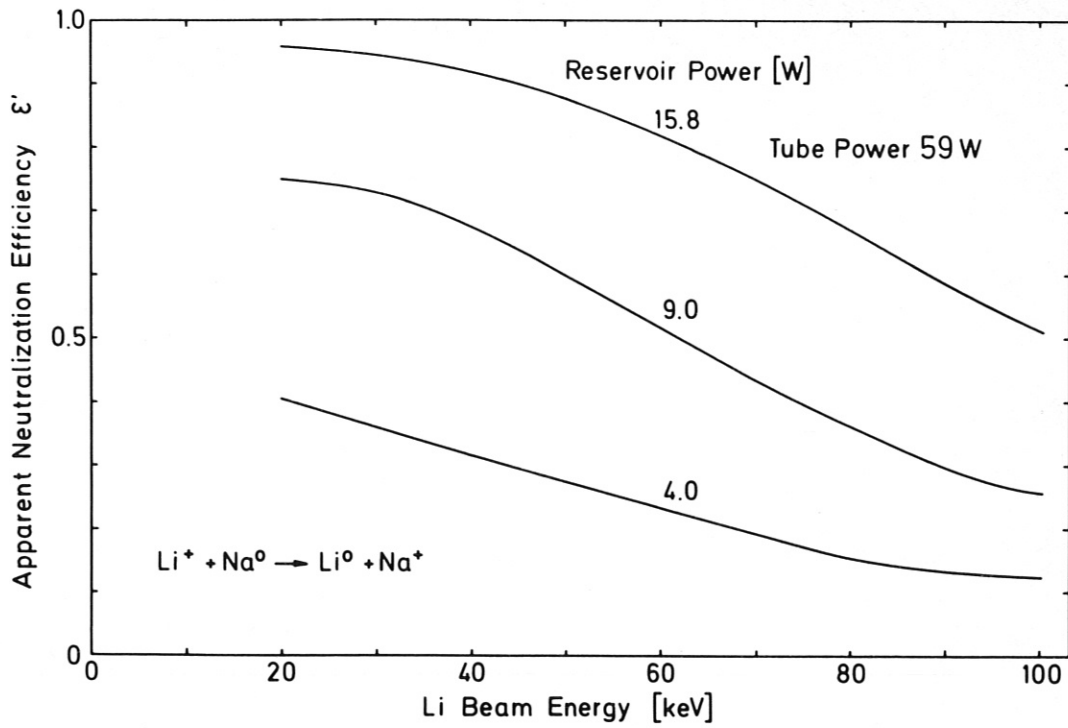


Fig.5 Apparent neutralization efficiency ϵ' vs. Li beam energy with reservoir power as a parameter.

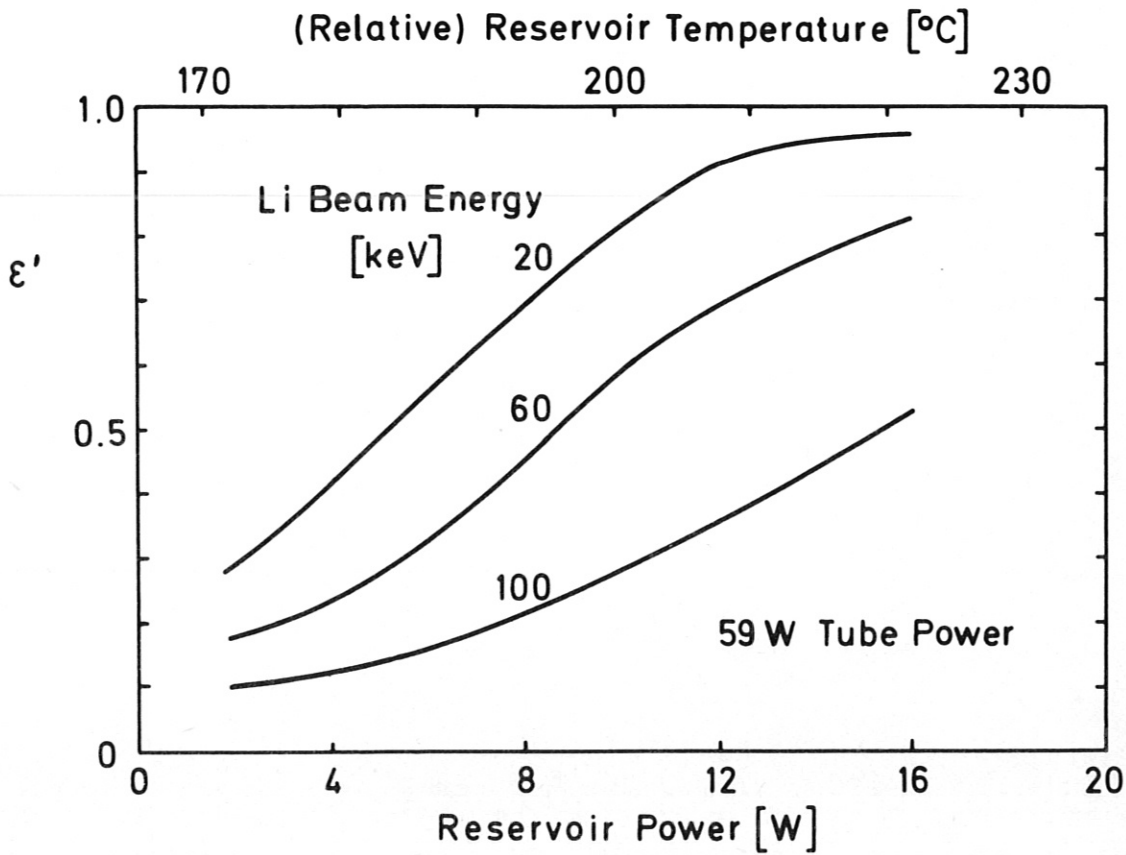


Fig.6 Apparent neutralization efficiency ϵ' vs. reservoir power and temperature with Li beam energy as a parameter.