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An Apparatus for the Production of
a Neutral Hydrogen Beam in the Energy Range
of 10 to 1000 eV

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Abstract

A beam of negative hydrogen or deuterium ions with an energy of 1 keV is extracted from an ion source. This beam can be decelerated down to 10 eV and is crossed through the resonator of a Nd-YAG laser. Due to photodetachment in the laser, a measurable part of the negative ion beam is neutralized. The resulting neutral beam of up to 1 nA is used for calibrating detection devices for fast neutral atoms.

INTRODUCTION

In fusion research the outflux of neutral particles from plasma experiments as a Tokamak or Stellarator is of great interest. A determination of the neutral flux yields information on ion temperatures and other parameters of the plasma/1/ and on all aspects of the plasma wall interaction. Therefore, and for many other purposes in basic atomic physics research, the energy analysis and detection of neutral hydrogen and deuterium atoms is necessary. For the development of detection systems a calibration source of neutral atoms with known energy and intensity is required. In addition, such a beam of neutral hydrogen would allow scattering experiments from solid targets. In a comparison with ion scattering experiments these would give more insight into the complicated processes determining the charge exchange processes during scattering /2, 3/.

Usually a neutral beam is produced by passing an ion beam of known energy through a gas cell. By charge exchange collisions with suitable gas atoms the ion beam is partly neutralized. Disadvantages of this method are: 1. The energy and angular distributions of the original beam broaden. This effect is increasing with decreasing energy and this limits the use of this technique to energies larger than 200 eV.
2. The absolute intensity of the neutral beam is hard to determine. We used this technique for calibrating our stripping cell neutral analyzer used for backscattering measurements /4/.

A different technique is to produce first a beam of negative ions and then photodetach the extra electron from the ion. The binding energy for the H^- (D^-) ion is 0.75 eV. Thus the photon energy of a Nd-Laser(1.17 eV) with 1060 mm wavelength is sufficient. The cross-section for photo detachment of the

H^- ion is $4\ 10^{-17}\ cm^{-2}$ for this wavelength /5/. Using these principles, a neutral beam was first realized by Van Zyl et al /6/. This technique avoids several disadvantages of charge transfer in a gas cell:

1. By the photo detachment process no momentum is transferred to the H^- ion. Therefore the created neutrals maintain their original energy and momentum, i.e. no energy or angular broadening of the beam occurs.

2. There exists only one binding state of the H^- ion and with the photon energy of 1.17 eV no excitation can occur. Thus all neutrals are created as ground state atoms and no disturbing metastables are present.

3. After passing the photo detachment region the remaining H^- ion beam may be deflected into a Faraday cup and be measured. Under some geometrical conditions (when the exit apertures are sufficiently large) the intensity of the neutral beam can be determined absolutely from the differences of the Faraday cup currents with the photon source on and off. This is essential for the absolute calibration of neutral atom detectors.

In this paper an apparatus is described which follows the guide lines of Ref. 6. Recently a similar apparatus was built elsewhere/7/. A schematic of the ion optical system for the production of the negative ion beam is shown in Fig.1. Negative ions are extracted from the ion source and accelerated to usually 1 keV beam energy. By an einzel lens the beam is made parallel and passed through a magnetic sector field. This serves for the selection of the desired ion species and removes the unwanted electrons from the beam. The magnet focusses stigmatically onto the entrance of the decelerating lens. The ion optics up to this point is essential the same as for the BOMBARDON described in Ref. 8.

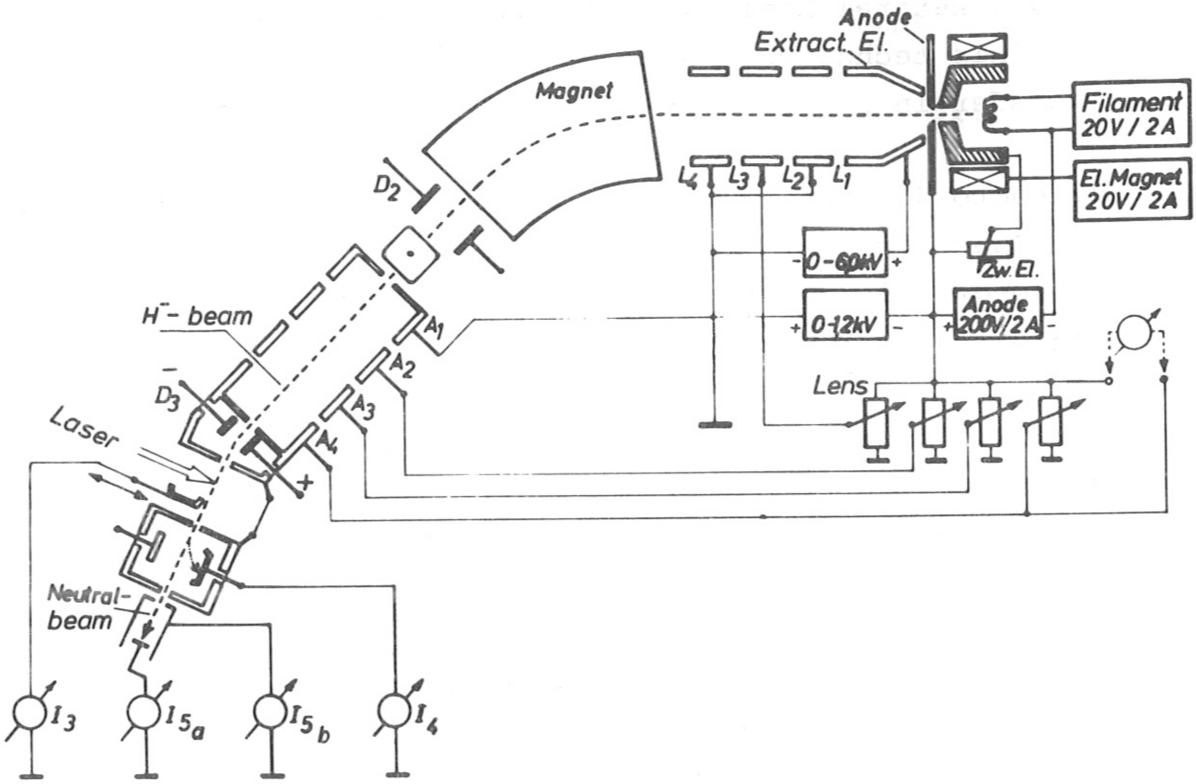

Fig.1: Schematics of the ion optical system

Two types of ion sources were used: 1. a Duoplasmatron and 2. a "Berkeley" source.

We used the same type of Duoplasmatron as in Ref. 8 with two modifications: The magnetic field was no longer produced by permanent magnets but by an iron encapsuled solenoid. This made it possible to optimize the magnetic field strength for a maximum H^- current. The magnetic field was made somewhat asymmetric with respect to the extraction electrodes. This is an old trick for extracting relatively more negative ions with respect to extracted electrons /9/. Practically this was achieved by an iron insert with an off-axis bore into the "Zwischen" (Intermediate)-electrode. It was found that a 3 mm bore which is 0.4 mm off the center line gave best results.

With optimal setting of arc, filament, and solenoid currents in the ion source, 3 keV extraction voltage and 1 keV beam energy an H^- beam of 1 μA at the entrance of the decelerating lens was achieved. The energy spread of the ions was measured with an electrostatic analyzer. With the ion source parameters for maximum H^- curent we found ΔE = 25 eV. By reducing the entrance aperture into the decel-lens which is situated close to the theoretical focus of the magnet the energy spread could be reduced to less than 10 eV. (This value corresponds to the energy resolution of the spectrometer). When the beam is decelerated to lower energies this energy spread is conserved, i.e. a beam decelerated to 10 eV has an energy spread of 100 %, which is certainly a poor value. Another disadvantage of the Duoplasmatron are some irreproducibilities of the discharge parameters.

As an alternative we used a source following a design from Berkeley /10/ (we call it therefore "Berkeley Source") which is similar to the commercial available Colutron. In Fig.2 a schematical cross-section is shown. As with the Duoplasmatron the ions are extracted from a plasma which is supported by a hot W-filament. The plasma chamber is lined by quartz-glass. The filament and the quartz glas liner can easily be exchanged by opening the cathode flange. The ions are extracted through a small hole (0,3 mm dia) in the anode made from Ta sheeting. The outer housing of the plasma chamber is of stainless steel. The insulating quartz liner has the effect, that the discharge is confined to a small area around the hole in the anode. This allows the extraction of beams with very low energy spreads. The distance to the extracting electrode can be varied. We have chosen 3 mm. The gas is fed into the source through a hole in the 6" main flange. Onto this flange the extraction electrode and the three electrodes of the Einzel lens are mounted by ceramic mounting studs.

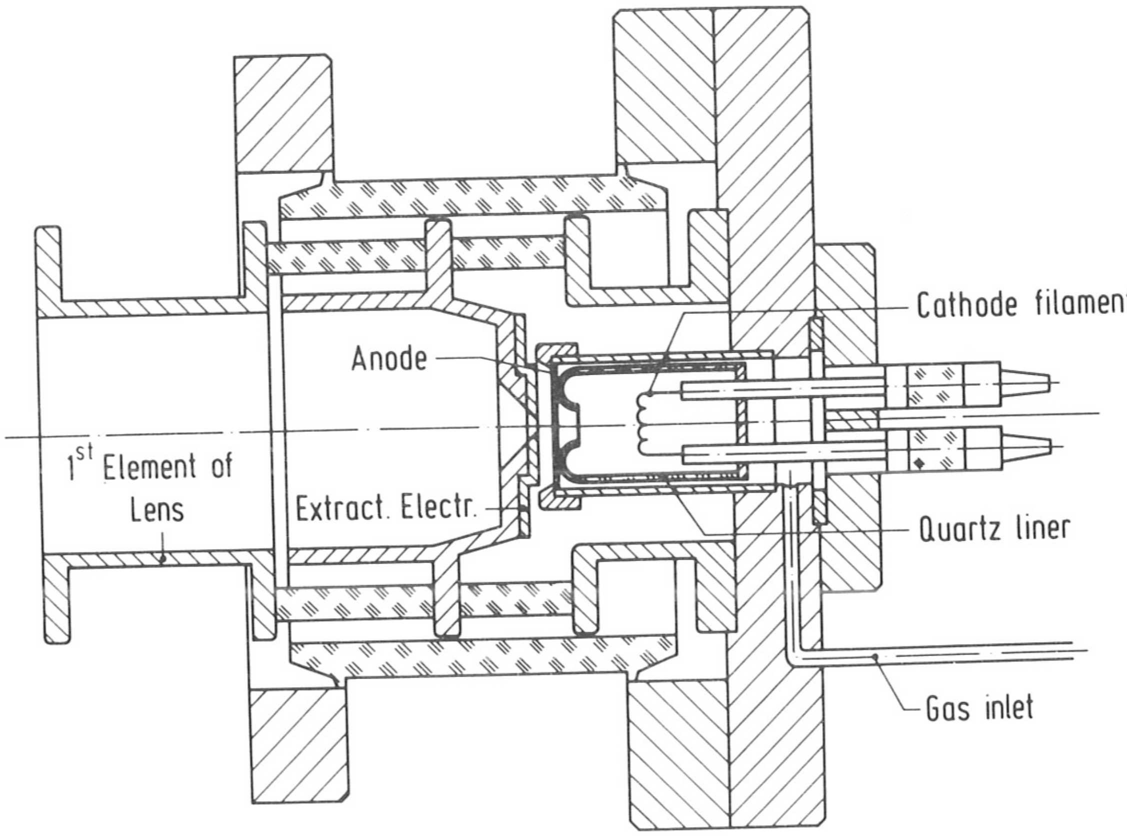

Fig.2: Berkeley Ion Source

This source is not yet tested systematically. But it was found that the source works best with a pressure of 0.5 to 1 mb, and an arc current of ∿ 1A. The beam which can be extracted is lower than from the Duoplasmatron but the focussable part of the beam seems to be much higher. This indicates that the energy spread of this source is smaller. However, this has not been measured so far. (For similar sources beam spreads of < 1 eV have been reported /7/).The reproduceable source parameters and stable burning are a big advantage.

The decelerating lens was designed according to the book of Harting and Read /11/. The lens geometry and the potential which have to be applied to the electrodes are chosen such, that the focus of the magnet is imaged into infinity, i.e. that a parallel beam is formed at the photo detachment region. However, in praxis the potentials are tuned to give maximum beam current which is not always at the calculated values. This might be due to the neglection of space charges in the calculation.

Before the beam enters the photo detachment region, it is bent by 10^{o} while it passes through at set of deflection plates. This is necessary to remove all neutrals with wrong energies which are created further upstream by collisions with the residual gas and with the apertures.

Two sets of deflection plates before and behind the magnet chamber are used for steering the beam through the apertures. Largest beam currents are obtained when the mechanical alignment is so good that no steering is required.

Behind the 10^{o} deflection is the photodetachment region. The ion beam enters and leaves this region through two 3 mm diameter apertures. The ion beam not neutralized by the photodetachment is deflected behind the second aperture into a Faraday cup where it can be measured, while the neutralized part of the beam maintains its original direction. It leaves the apparatus through the exit aperture, which can be chosen according to the requirements of the specific instrument.

The vacuum is obtained by a 3 stage differential pumping system. In the first stage between ion source and a 10 mm diameter aperture at the entrance of the magnet chamber the main gas load from the ion source is pumped by a 450 l/s turbomolecular pump (Leybold-Heraeus). A second pump of this type sucks on the magnet chamber, which is separated from the decel-lens region by the 5 x 10 mm aperture at the focus of the magnet. The last stage which contains the decel lens and the photodetachment region is pumped by a 360 l/s turbopump. The pressures during ion source operation are 10^{-5} Torr in stage 1, 10^{-7} in stage 2, and 2 10^{-8} in stage 3.

As a light source for the photodetachment a Nd-YAG Laser was chosen. This laser delivers IR-radiation with a wavelength of 1060 nm which corresponds to a photon energy of 1.17 eV. This is well above the affinity level (0.75 eV) of the H^- ion and around the broad maximum for the photodetachment cross-section of H^- /5/. A commercial available laser (Holobeam mod. 2660) is used. This gives a power output of 100 W c.w. through the 10 % transmitting front mirror. For this output power level an input power of $\sim$ 6 kW is required for the krypton arc pumping lamp.

The photodetachment yield is proportional to the photon density in the interaction region of the ion and photon beams. Within the laser resonator the photon density is 9 times as large as outside the laser, because only 10 % of the laser beam is transmitted through the front mirror. Therefore it is advantageous to pass the ion beam across the laser resonator. This requires, however, that the vacuum tubing has to go through the laser. At least one vacuum window is required if the front mirror is mounted inside the vacuum /7/. Because of possible vibrations due to the turbopumps we decided not to have any mechanical connection of the laser system with the vacuum system. Thus the front mirror is outside the vacuum and two windows are required. With this arrangement it is possible to align the laser separately. The laser as a whole can then be adjusted with respect to the ion beam.

Due to the thermal lensing action of the laser rod at high power levels the laser output power decreases when a certain temperature is reached and when the front mirror is too far away from the laser head. The maximum possible laser output power as a function of the distance between laser head and front mirror is shown in Fig.3. From this it is clear, that the laser resonator should be made as short as possible.

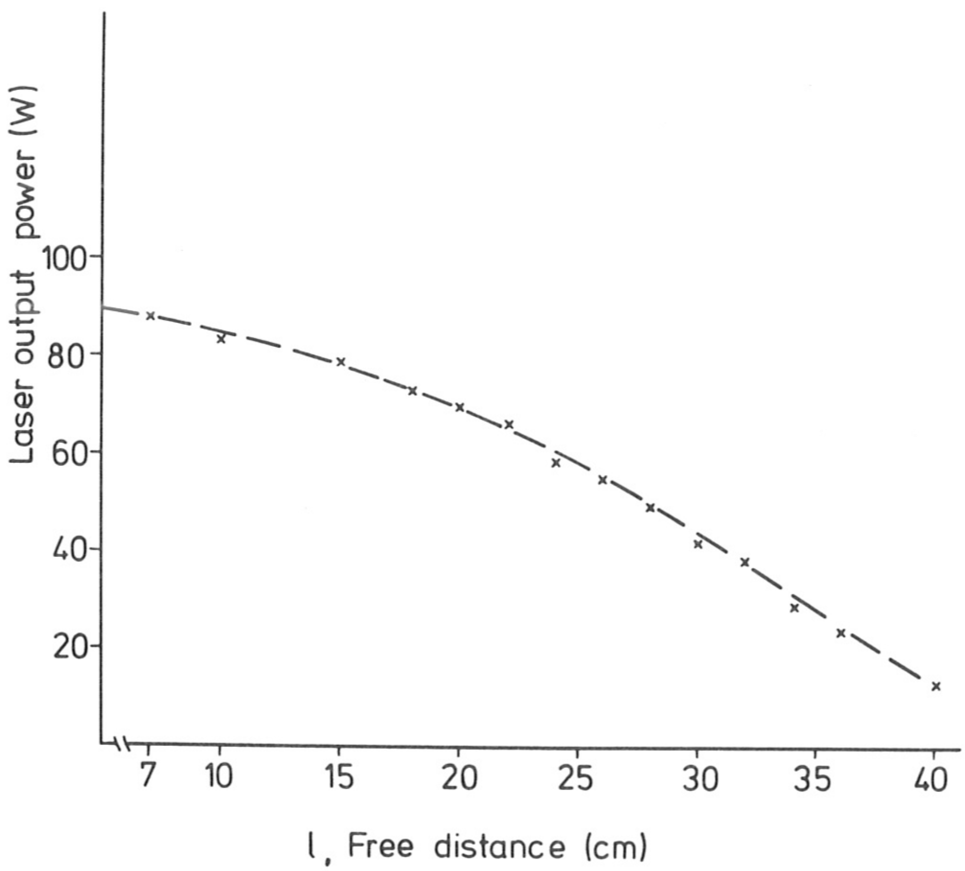

Fig. 3: Maximum possible laser power output or a function of the free distance between laser head and front mirror.

The final design of the photodetachment region is schematically shown in Fig.4: The window at the front mirror is mounted on a tube which extends inward from the flange as close as possible to the ion beam. The ion beam, however, has to be shielded, because of electrically charging of the window which deflects the beam. In our apparatus the actual distance of the laser head to the front mirror length of the

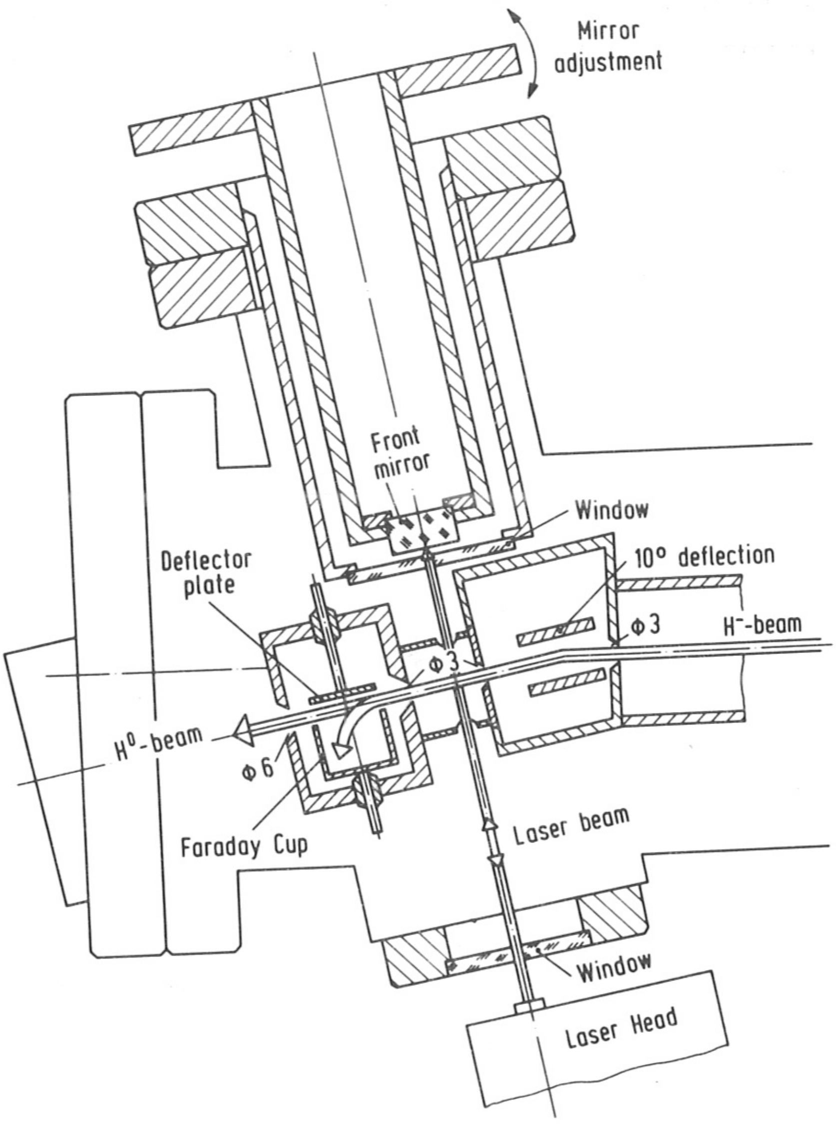

Fig.4: Interaction region of the ion and laser beam

laser resonator is 115 mm. It contains two antirreflection coated windows. Operation with a 100 % reflecting front mirror would be possible. With 90 % transmission, however, it is still possible to monitor the laser output power. With the present arrangement we achieve 60 W output, instead of 100 W with the front mirror close to the laser head.

For the determination of the produced neutral beam current the residual negative ion beam is deflected into a Faraday cup behind the 3 mm dia. exit aperture of the photodetachment region. The neutral current is the difference between the ion currents with the laser on and off. The neutrals are assumed to follow the same trajectories as the ions would do if they would not be neutralized. For a sensitive measurement the laser beam is mechanically chopped (30 to 200 Hz, 50 % duty cycle) by a sector disc which runs through the laser resonator and the neutral current can be measured by lock-in techniques. This absolute determination of the neutral beam intensity is only valid as long as one can be sure that all neutrals behind the Faraday cup reach the place where the neutral beam is used. This is true when the negative ion beam can be focused to this place and nothing is lost at the aperture behind the Faraday cup. In most cases we use an exit aperture of 6 mm dia, for which it was made sure that no part of the negative beam hits the rim. Thus, only rather large area (> 6 mm dia) detection devices can be calibrated absolutely.

Performance

For an estimate how much of the ion beam should be neutralized while crossing the laser beam, we consider the probability for photodetachment of a single H^- ion

$$P = \frac{1}{v}\int_0^d \sigma\, \varnothing(x)\,dx$$

where v is the ion velocity, σ is the cross-section for our wavelength, and $\varnothing(x)$ is the photon flux density along the ion path in x-direction /12/. For simplicity we assume that the flux density is constant over the whole laser beam diameter of d = 3 mm. Hence it is

$$P = \frac{d}{v}\,\sigma\,\varnothing.$$

A single photon has the energy of 1.17 eV $\hat{=}$ 1.875 10^{-19} J. With 30 W laser output power (due to the chopper we have only half the c.w. power) we have a photon current inside the resonator of

$$I_p = 2.89 \times 10^{21} \text{ photons/s}$$

This results in a photon flux density of

$$\emptyset = 4.077\ 10^{22} \text{ photons/cm}^2 \text{ s.}$$

With $\sigma = 4 \times 10^{-17}$ cm^2 /5/ we can expect a neutralization probability of

$$\begin{aligned} P &= 0.11 && \text{for } 10 \text{ eV} \\ &= 0.022 && \text{for } 250 \text{ eV} \\ &= 0.011 && \text{for } 100 \text{ eV } H^- \text{ ions.} \end{aligned}$$

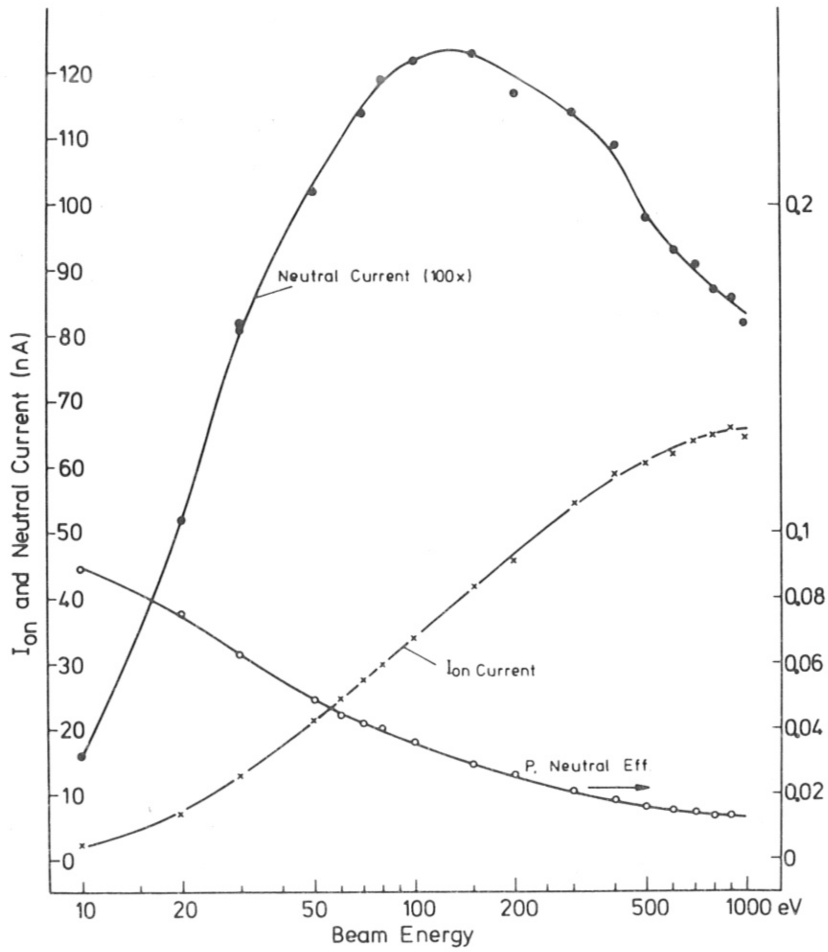

Fig.5: Ion and neutral currents achieved with the Duoplasmatron source versus beam energy $P = J^o/J^4$ given the neutralization probability.

In Fig. 5 is demonstrated, what we have got using the Duoplasmatron source. The ion current was directly measured in the Faraday cup (J_4 in Fig.1) while the neutral current (in nA equivalent) was determined using the lock-in amplifier. It is seen, that the experimental neutralization probability J_0/J_4 is quite close to the estimate given above. The ion current decreases with decreasing beam energy but as P is increasing the neutral beam intensity is maximal around 100 eV.

The apparatus was first being used for the calibration of a detector for the LENA (Low Energy Neutral Analyzer) for ASDEX. Figure 6 shows schematically this detector:

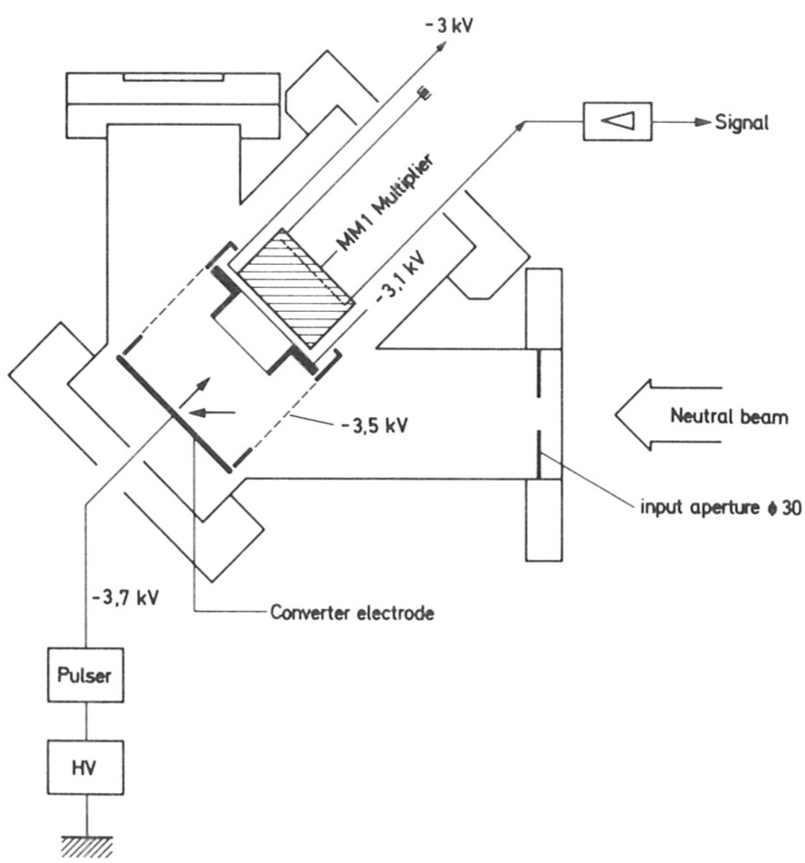

Fig. 6: Neutral particle detector for LENA

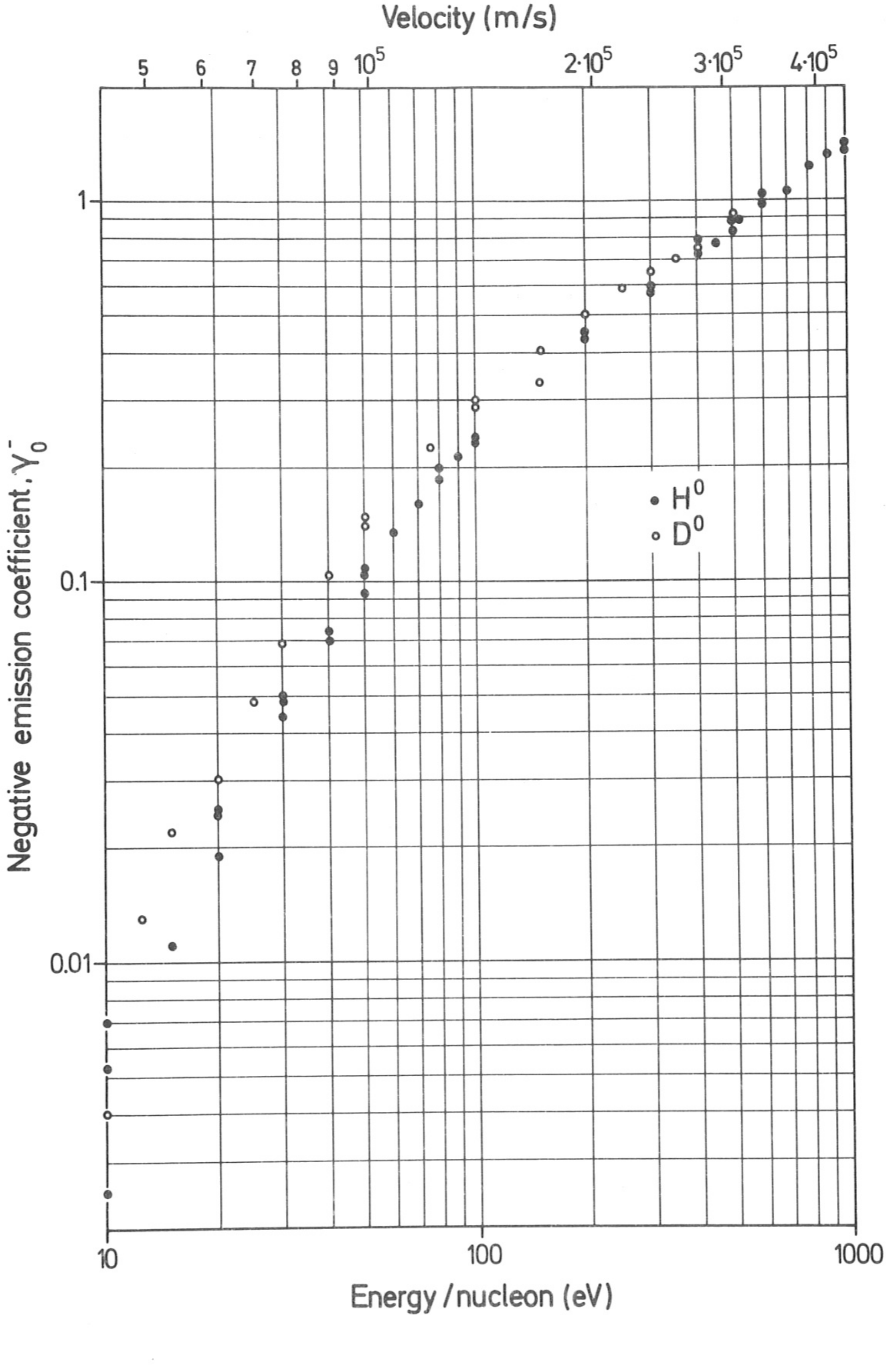

Fig.7: Negative emission coefficient for H^O and D^O impinging on the Cu converter electrode of the detector shown in Fig. 7.

The converter electrode is hit by the neutral particles which release negative secondary particles. These are accelerated and focused to the entrance of an open multiplier (Johnston MM 1). The yield of secondary particles per incident neutral was determined by measuring the neutral current as described above and the negative current leaving the converter plate, i.e. a positive current through an electrometer connected to ground. With the correct voltages at the auxiliary electrodes the total charged particle current leaving the converter electrode could be collected at the entrance of the multiplier. As this detector has a large entrance aperture (30 mm dia) the conditions for determining the neutral current absolutely are fulfilled. The result is shown in Fig.7 for H^o and D^o. The negative yield is plotted for H and D at equal velocities.

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