FINDING THE OPTIMUM FREQUENCY AND THE Hminus DISTRIBUTION IN THE HERA RF- VOLUME ION SOURCE

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Abstract. The HERA RF-Volume Source is the only source available that delivers routinely an H^- current of 40 mA without Cs.
The dependency of the quality of the H^- beam on the frequency was investigated. A frequency range of 1.65 – 9 Mhz was scanned and the emittance was measured for several H^- currents up to 40 mA.
The production mechanism for H^- ions in this type of source is still under discussion. Laser photodetachment measurements have been started at DESY in order to measure the H^- distribution in the source. The measurements have also been done under extraction conditions at high voltage.
The results of the measurements with and without extraction are a basis for the development of a theory for the transition between plasma and vacuum (sheath), a cornerstone for beam transport programs.
Knowledge of the H^- distribution and where they are produced makes further source improvements possible.

INTRODUCTION

The first RF driven volume source (1) was built in 1991 at LBL with an RF antenna immersed in the plasma. It became the prototype for the SSC (2) source which was later cesiated. The amount of Cs needed for this type of source is so low that it is possible to use Cs dispensers mounted on a collar around the plasma aperture. The source installed at SNS (3) is similar with a high duty cycle of 6%.
The DESY source (4) was modeled on the SSC source. It has a low duty cycle (0.12 %). 80 mA were reached with a tantalum collar (5) and the same internal antenna type which was used for SSC and LBL designs. It turned out that these antennas contained potassium (K) which works similar than Cs.
For reliability reasons the RF coupling coil was placed behind a ceramic outside of the plasma (6) (Fig. 1. and 2.). More than 50 mA were recently reached with this source.

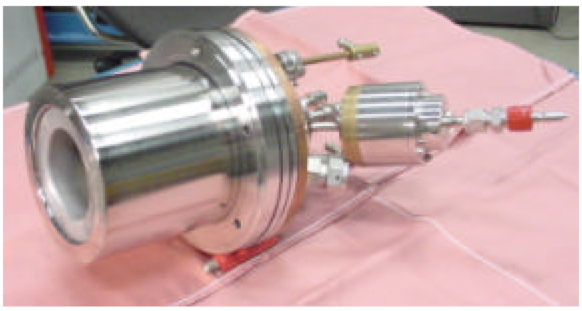

FIG. 1. The Discharge chamber of the DESY volume source with an external RF coupling outside of the plasma.

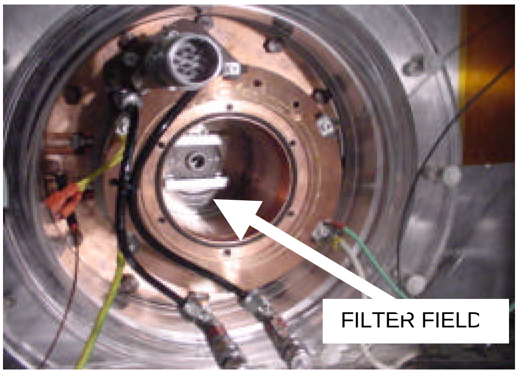

FIG. 2. Filter field magnets, collar, and plasma aperture of the DESY volume source.

The lifetime of the system is more than a year compared to 500 – 700h for a filament system. The RF volume source works best with a starter system. At DESY a tandem source is used for this purpose.

Finding the optimum frequency for an RF volume source

Accelerator users need a maximum H^- current and a low beam emittance. For a low emittance, the H^- have to be delivered at a low plasma temperature. According to the volume process a high H^*_2 production is necessary for a maximum H^- current. There are at least two reasons for a frequency dependence :

1.) The optimum energy level for producing H^*_2 has to be reached in half a period. When the time is too short (frequency too high) it is possible to increase the input power but this increases the plasma temperature.

2.) The plasma penetration is different due to the frequency dependent skin effect.

Determining the parameters of the RF coupling coil

The magnetic field H and the electric field E inside of a coil (see Fig. 5.) can be expressed

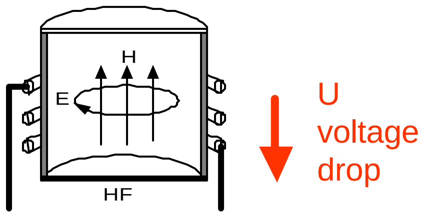

FIG. 3. Schematic of RF source, showing RF discharge chamber, coil , coil voltage drop and fields

with the following (7) :

$$H = J_{RF}\frac{N_{COIL}}{\sqrt{l^2_{COIL} + 4R_{COIL}}}$$

$$E = \frac{1}{2} r\omega B_0 \sin\omega t$$

where l_{COIL} and R_{COIL} are the length and the radius of the coil. N_{COIL} is the number of coil windings. I_{RF} is the current delivered to the source by the transmitter and the transforming network. The electric field depends on the magnetic induction $B_0 = \mu H$ and r the radial distance from the center of the coil. The voltage drop over the coil depends on the frequency ω and the inductance L. The dependenc is given by :

$$U = J_{RF}\ \omega L\ \ ;\ L \approx N_{COIL}^2$$

The electric field produced by this drop can be reduced by using special winding techniques. A high field will disturb the plasma. It is important to note that the H field depends linearly but the voltage drop quadraticly, on the number of windings

Coupling of the transmitter power to the plasma

The cooperation between DESY and Frankfurt University made it possible to bring a transmitter tunable with four coils and a capacitor in the range between 1-13 MHz to DESY. A coupling box with a variable transformer and a tunable capacitor (Cres) was built by DESY. Cres forms together with the coil inductance a series resonance circuit (Fig. 4.). The power delivered to the source is influenced by the skin effect, parasitic capacitances and the proximity effect. Power measurements were done with a dual directional coupler. Measurements directly at the coil turned out to be very difficult due to the nonlinear characteristic of the source load and the phase sensitivity of the parameters.

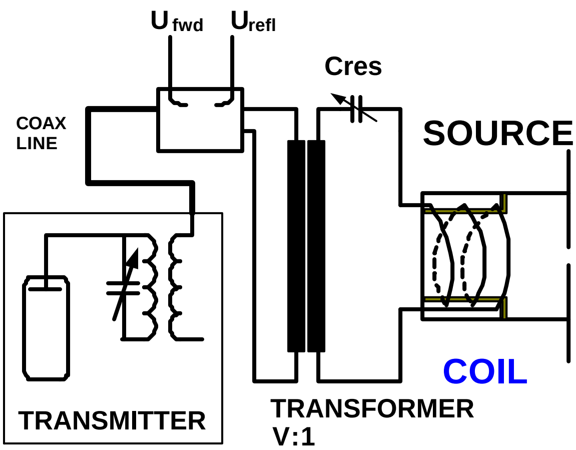

FIG. 4. Coupling of the RF transmitter to the source

H^- Current vs. RF power for different Frequencies

Fig. 5. shows the frequency and RF power dependence of the H^- current. It turns out that with the set up used a frequency range between 2 MHz and less than 4 MHz demonstrates the best power efficiency. For higher frequencies the plasma penetration is reduced due to the skin effect, the voltage drop over the coil increases, parasitic capacitances and the proximity effect become more effective. In the low frequency range the voltage drop and the electrical field is reduced. These two effects can be compensated partly by a higher number of windings.

Unfortunately it is not possible to compare these measurements with those of the SNU (8) (13,56 MHz) and the two ECR type sources at SACLAY (9) and Yamaguchi University (10) both at 2.54 GHz, because their RF power and the currents are much lower.

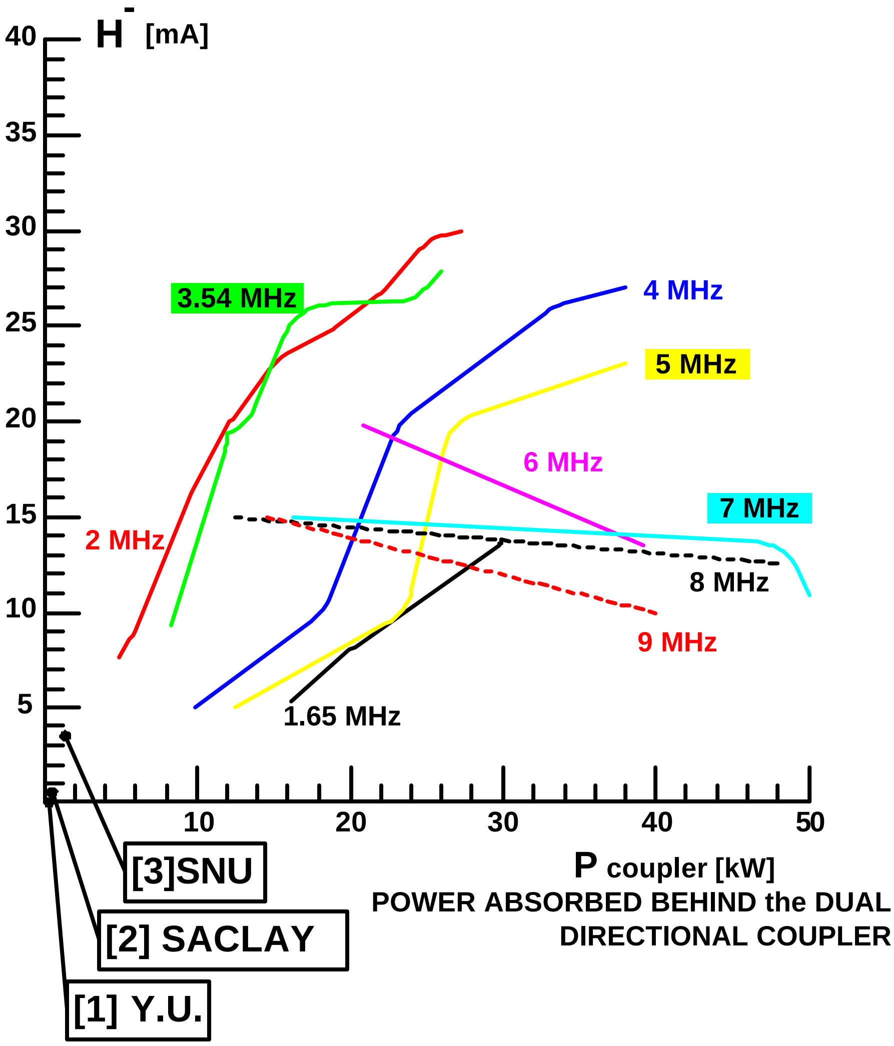

FIG. 5. Frequency and RF power dependence of the H^- current

Measurement of the emittance vs. frequency

Fig. 6. shows the frequency and H^- current dependence of the 90% rms emittance. The dependence on the H^- current was used for comparison because this is a parameter which can be measured easily. The curves demonstrate almost the same characteristics. This might be due to a slight change in the position of the beam. Only the 3.54 MHz curve seems to be different. Note that it is difficult to keep all parameters during the long emittance measurements constant. Especially the gas pressure and the tuning of the series resonance seem to be very sensitive.

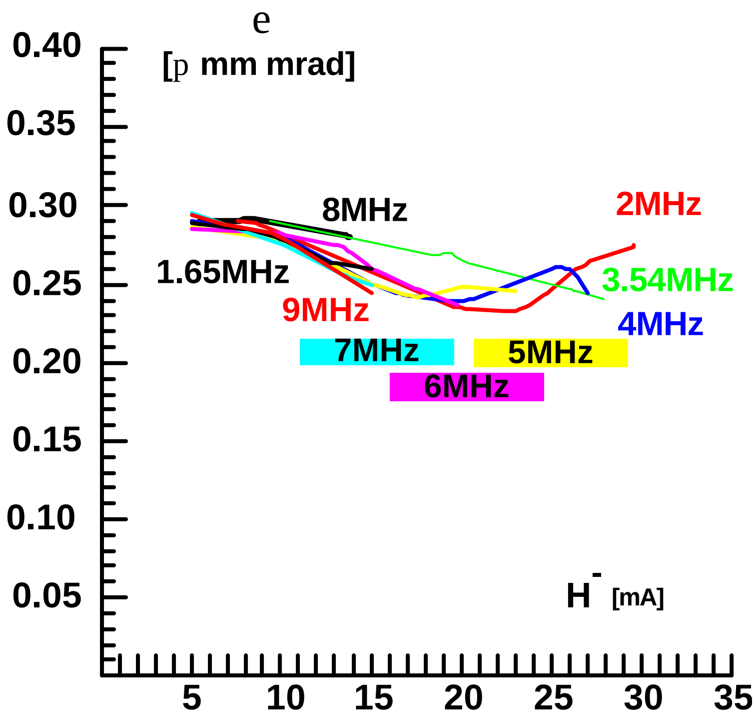

FIG. 6. Frequency and H^- current dependence of the rms emittance

H^- Current vs. RF power for different frequencies and numbers of windings

Coils with 6.5, 20 and 40 windings were used in order to measure the frequency dependence of the H^- current (see Fig. 7.). It was not possible to get a stable performance of the source for all coils at higher frequencies.
A power of 26 kW was reached for all coils at the frequencies 1.65 MHz and 2 MHz (Fig. 8). This made it possible to plot the frequency dependence of the H^- current with the number of windings as parameter and the winding dependence with two frequencies as parameter. Fig. 9. demonstrates the improvement of performance at lower frequencies with the number of windings ($H \sim N_{COIL}$). It was not possible to reach the 6.5 wdg. values. In Fig. 10. the reduction of the H^- current due to the voltage drop $U \sim N_{COIL}^2$ is demonstrated. It reaches values of U~18 kV.
In further experiments a shielding of the electrical field will be applied.
Adding up all improvements and using a high power transmitter we were able to reach a peak H^- current of 61 mA with an average of 58 mA (see Fig. 11).

FIG. 7. RF coupling coils with 6.5 and 40 windings

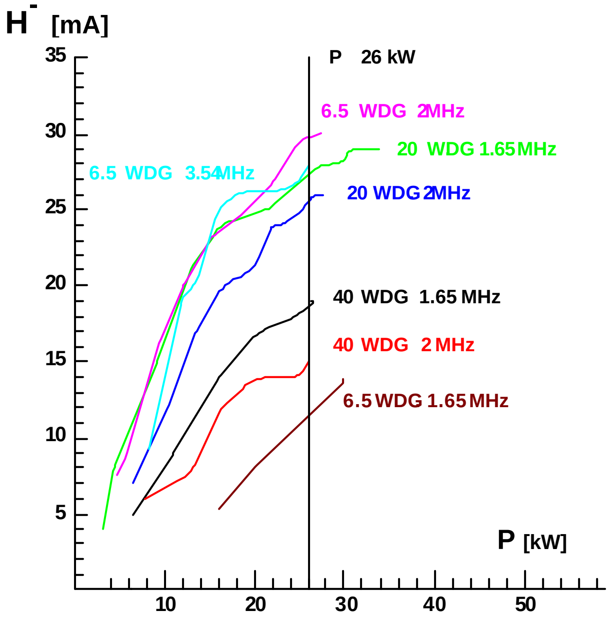

FIG. 8. H^- current dependence on RF power and the number of windings.

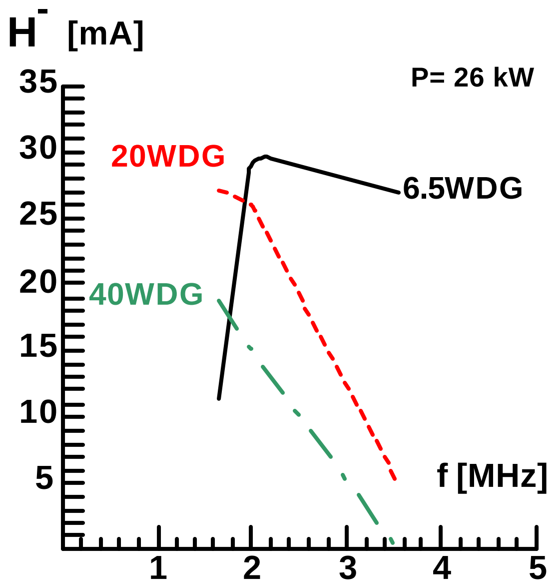

FIG. 9. H^- current dependence on frequency with the number of windings as parameter at 26 kW

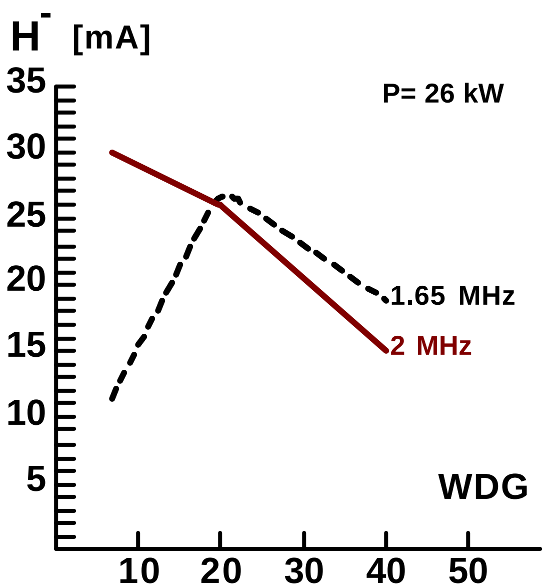

FIG. 10. H^- current dependence on the number of windings with the frequency as parameter at 26 kW

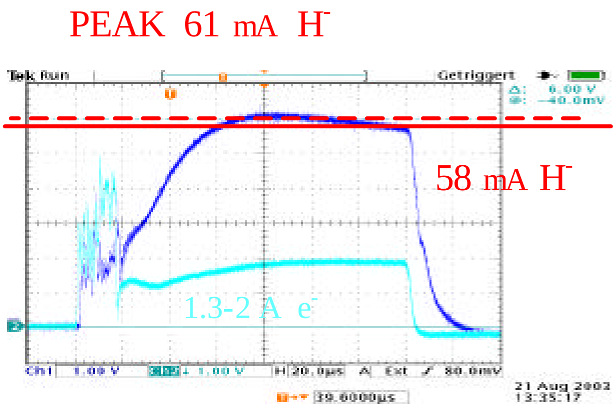

FIG. 11. H $^-$ current at the source exit toroid and the electron current.

Cooling section between discharge chamber and filter field

Cooling sections with the length of 0.5, 1, 1.5 and 2 cm were added between the discharge chamber and the filter field. The usual multi cusp field was kept. It turned out that the brightness=I_{H^-} /εy can be increased with insertions for H $^-$ currents higher than 40 mA. However the maximum of the H $^-$ current is reduced.

PHOTODETACHMENT MEASUREMENTS

Photodetachment measurements in order to measure the density of negative ions have been done as early as 1969 (11). First density measurements of H$^-$ are reported in 1979 (12). In the HERA source a modification of a technique with a cylindrical metal probe (langmuir probe) aligned parallel to a laser axis (13) was used. The details of the source are given in several papers (14),(15),(16).

MEASUREMENT SET UP

The power applied at the RF coil of the HERA H $^-$ source is pulsed. With a positive bias (U_{LP}) of 5V close to saturation one draws an electron current to the tip of the probe. This current (I_{LP}) is measured with a toroid (see Fig.12). The current signal is shown in Fig.13a. The affinity of the electron attached to the hydrogen atom is with 0.75eV very low (11). By photodetachment $H^- + h\nu = H + e^-$ an increase in electron density is produced.

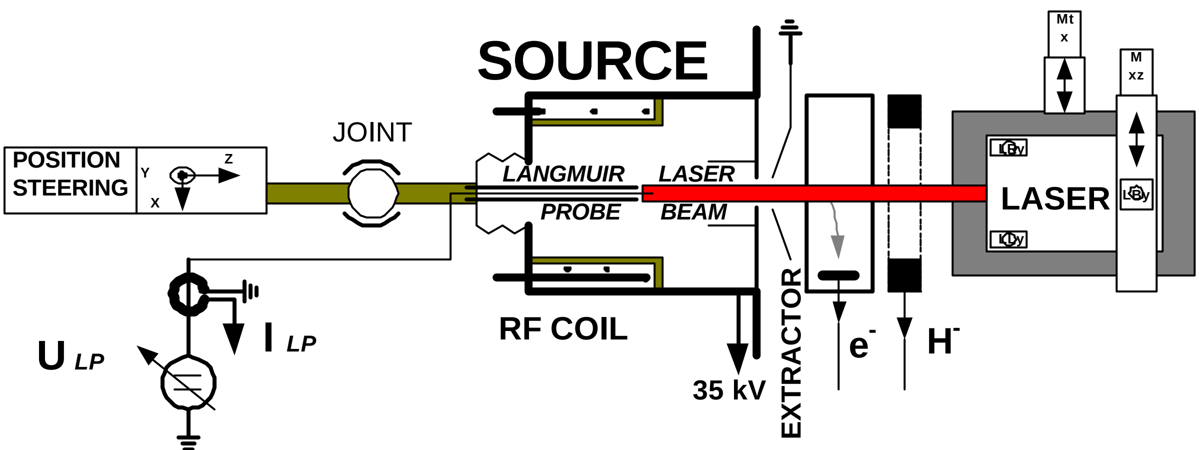

Figure 12: HERA RF source with mounted langmuir probe on the back side and a laser beam shooting through the extractor hole.

To clearly interpret the signals it has to be made sure that no other photon processes like photoionisation take place. Fig. 13b shows the increase in electrons detected when a 9 nsec, 1064 nm puls of a Nd: YAG laser travels on the axis of the source. The maximum pulse energy of our laser was 650 mJ per pulse. The 8 mm ∅ laser beam was compressed to 3mm ∅ with an optical system.

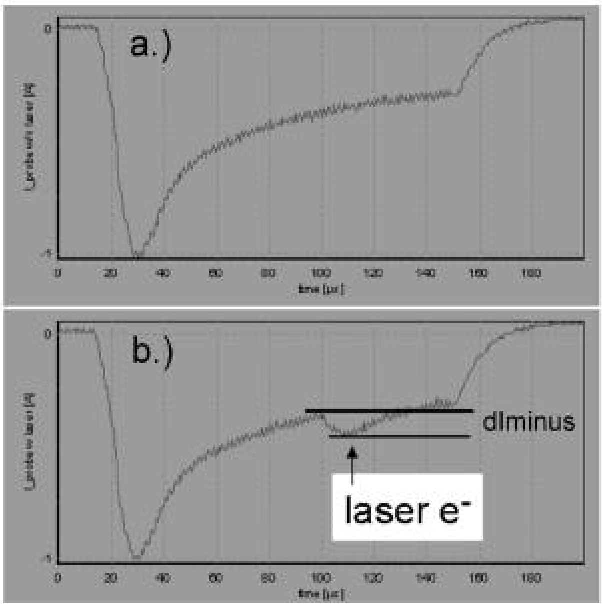

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Figure 13: Current pulse of the Langmuir probe (I_{LP}) without laser beam (a) and with photo detached electrons (b).

The beam was dumped on the probe or on a ceramic dump surrounding the end of the probe. A set up where the laser beam is dumped outside of the source is given in (17). The probe tip and inner conductor are a molybdenum wire of 0.4 mm ∅. The center wire is shielded by a metal tube which is completely isolated from the plasma with sealed ceramic tubes (see Fig. 14).

Due to the environment there is noise on the signals in Fig. 13. By averaging over many pulses it was possible to get very stable values.

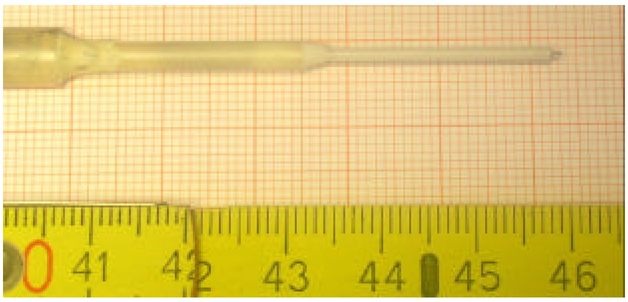

Figure 14: Ceramic shielded probe with tip

We tried different ways (18) to detect the increase in the number of electrons due to the laser beam. First the signal without laser beam was subtracted from the signal with laser beam. It turned out that detecting in the same pulse the difference between maximum and the minimum before the laser starts delivers the same results.

The laser beam was fixed on axis of the source. The probe tip was moved step by step in rectangular planes perpendicular to the beam axis (see Fig. 12). The x and y movement is done by turning the probe in a joint the z motion by pulling the probe in and out. The movements in x, y and z are done with a three table system. A long bellow is used for transforming the movements into the vacuum.

The size of the planes over which measurements were done varied from 4mm x 4mm in the collar area to 10mm x 10mm in the RF coil range and had in the final part of the source a size of 6mm x 6mm. All measurements were done with a 0.5 mm step size. The z planes were measured in 5mm steps.

RESULTS

Fig. 15 gives a 3D sample presentation of typical H^- intensities measured on selected rectangular areas along the source.

It was possible to associate measurement patterns to different zones of the source. The H^- intensity (Nh^-) is proportional to the additional electron current delivered due to the laser pulse . The Nh^- measurements were taken along the central axis of the source in arbitrary units. Measurements were taken at 0 V and at 10 kV extractor gap voltage.

Strong Cusp Magnet Field Area

In the range between z=65mm and 95mm a strong multicusp field is present in the source. Only a small maximum was detected in an area of about 1.5mm times 1.5mm which is a factor 2 smaller than the laser beam diameter. Significant peaks with a Nh^- value around 1 were measured.

RF Field Area

Between z=100 mm and 130-140 mm a strong RF field is applied to the plasma. The cusp field is reduced and the dipole filter field starts only at the end of the range. One finds now laser produced electrons in a circle with 10mm diameter. A plateau is formed and in addition there are spikes. The spikes become more numerous when the acceleration voltage is applied. Apparently the freed electrons are accelerated by the RF field and this movement is modulated by the acceleration voltage. In this range a maximum Nh^- value of 2.28 was found.

Filter Field Area (in front of the collar)

A dipole field is applied which has a maximum of about 20 mT at z= 157 mm and goes to zero in the middle of the acceleration gap. The plateau becomes lower which could be due to a reduced RF field. Just in front of the collar the size of the measurement plane was reduced in order to avoid damage. Here the H^- densities were less than half the maximum values.

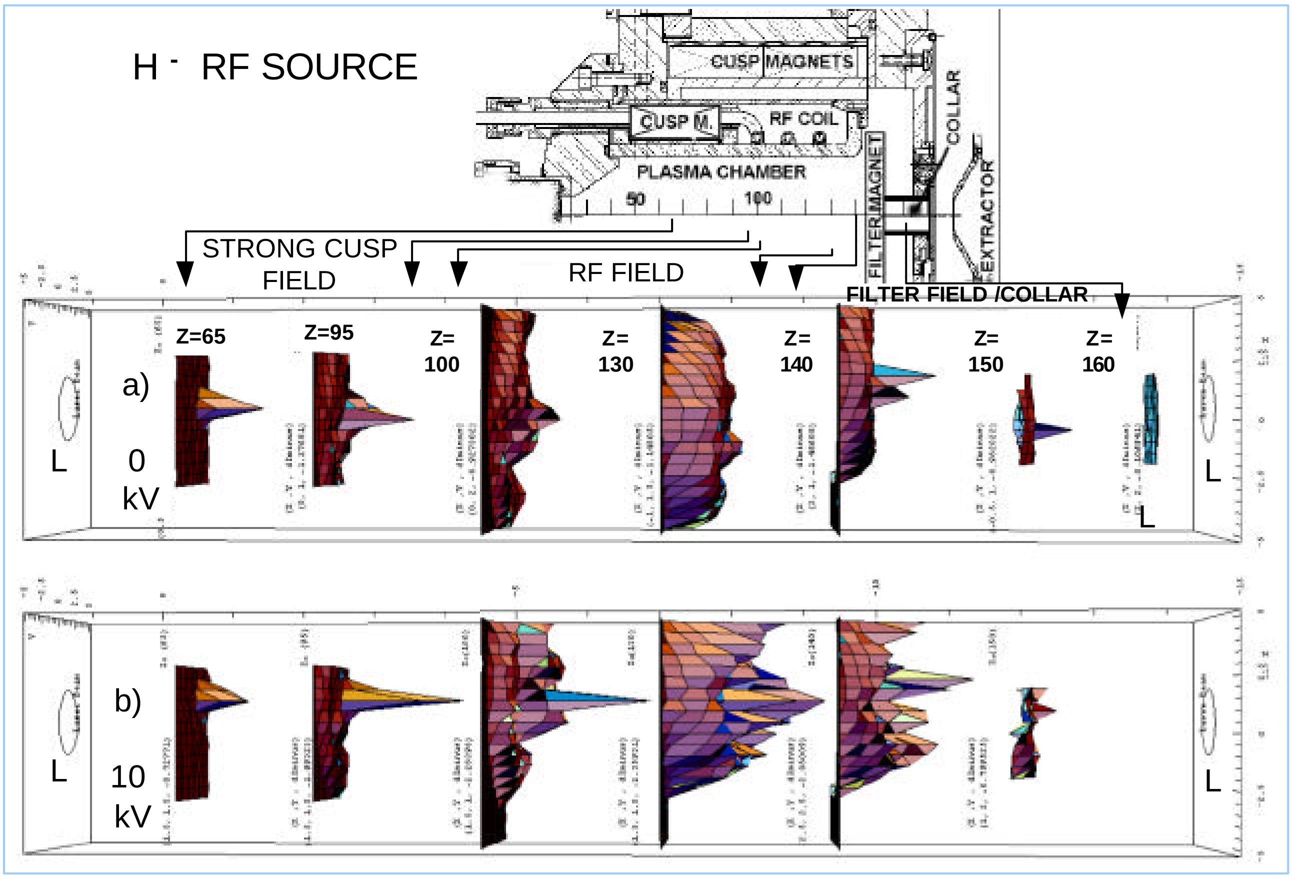

Figure 15: H $^-$ intensities along the source axis without extractor gap voltage (a.) and with 10 kV applied (b.). L marks the laser beam diameter.

Collar Area

In this region only one measurement was done without acceleration voltage due to sparking which occurred under high voltage. With the 6.5 mm plasma aperture the plasma density is here reduced. The H $^-$ density (N_{H^-}) is only about 5% of the maximum values detected. In case of an applied acceleration field there would be a competition between the field from the probe tip and the accelerating field.

Acceleration Voltage (On/Off)

Contrary to expectations a large intensity change was found when an extraction voltage of 10 kV was applied. This difference is most obvious in the RF field area. The voltage was applied in the usual operation mode with extractor at ground and the source at high voltage. The mechanic for the probe was grounded and isolated from the probe and source bucket.

Alignment

In the strong cusp magnet field area the position of the maximum intensity varies only 0.5 mm, the step size. In the RF field area the variation is bigger and with HV applied many peaks occur. In case of the filter field range without HV the adjustment was lost due to a power failure.

PHOTODETACHMENT AND H^- GENERATION UNCERTAINTY

The biased tip of the Langmuir probe collects the photodetached electrons which are seen as a local maximum within about 5 µsec (see Fig. 13). If there is a plasma potential with a gradient present or if there is an RF field there will be an uncertainty. Electrons detached in the 9 nsec laser light channel flash can be driven to the probe or away from the probe dependent on the plasma gradient. A contribution to the dIminus maximum will depend on distance of the electrons from the tip and their speed. A local maximum of the plama potential will collect additional electrons from all sides a gradient plasma mainly from lower side. A complicated plasma potential surface can result in very different pictures of the measured dIminus.

The field gradient due to the RF field has a similar effect. Dependent on the RF frequency the electrons will be moved several times back and fore before it hits the tip. As seen in Fig. 15 & 16 a transversal component is added to the picture in the area of high RF levels.
In a low density plasma there is a strong effect of the extraction voltage on the plasma potential. Measurements of the HERA source showed only a small influence of the extraction voltage but a big one of the collar potential (16).

Uncertain is also were the measured H^- are produced if there is a plasma gradient or a RF field. They are also moved by these fields and within the pulse of 100 µsec there is plenty of time to redistribute.

The RF source, four distributions of photodetached electrons and the plasma potential are shown in Fig. 16. The photodetached electrons are concentrated were the plasma potential has its maximum. Photodetaced electrons and H^- are moved to this spot by the voltage gradient.

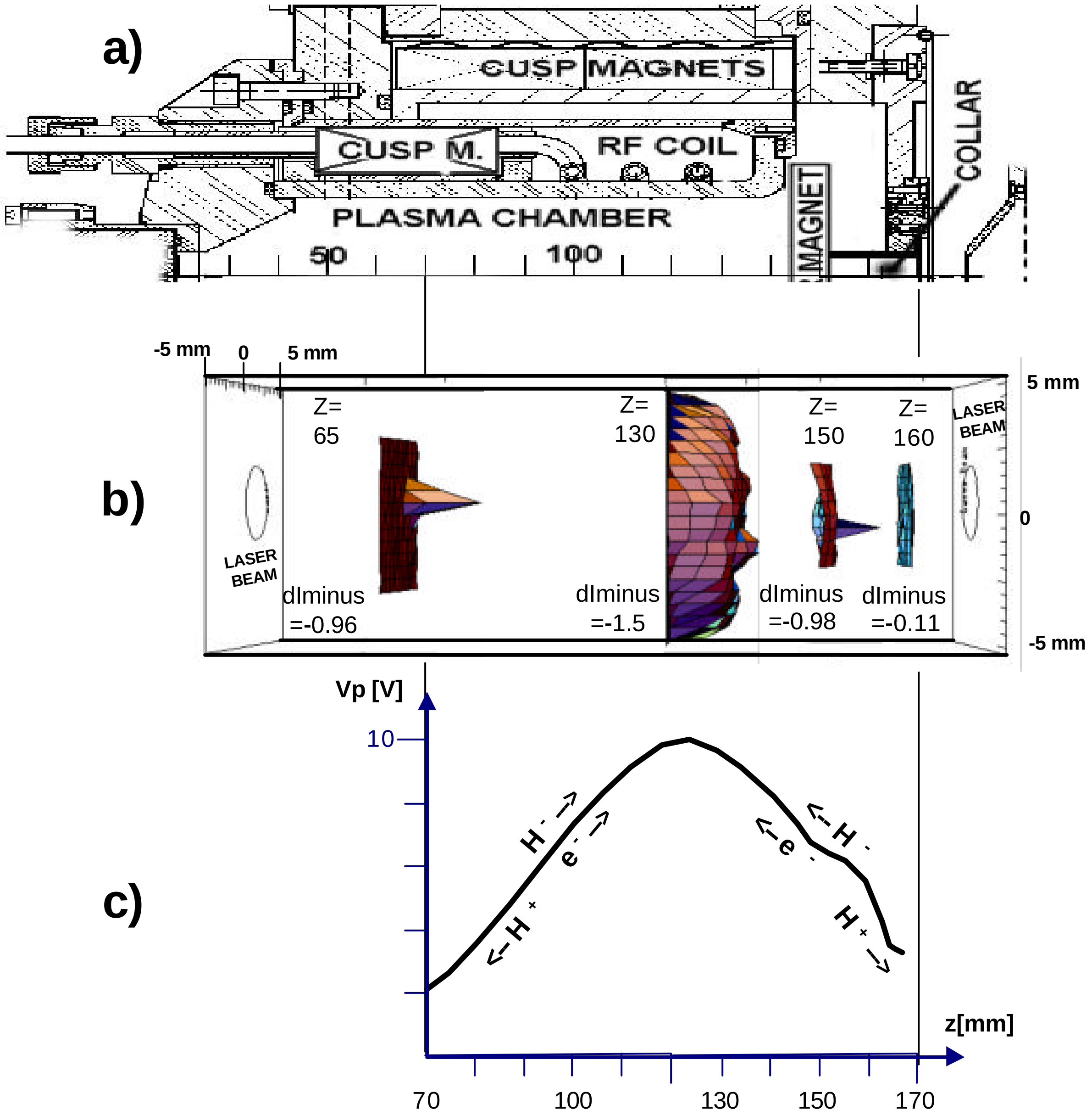

Figure 16: a) RF source b) Photodetached electrons c) Plasma potential . The photodetachment electrons are concentrated were the plasma potential has its maximum. photodetaced electrons and H^- are moved to this spot by the voltage gradient.

CONCLUSIONS

Photodetachment measurements of the H^- ions show that the extraction voltage has an unexpected effect on the H^- distribution in the plasma. The photodetached electrons and the H^- are strongly influenced by the different magnetic fields and the RF which is coupled into the source plasma which results in the shown plasma potential. A 20mm shift of the plasma potential maximum to the entrance of the collar should improve the H^- distribution and lead to a higher extracted H^- current.

Care has to be taken that the electrons which attach to the vibrationally excited hydrogen molecules keep their temperature.

It will be important to study the H^- distribution not only on axis but in the whole source.
The magnetic and RF fields together with the laser light should be carefully measured. Varying the filter field and observing the change in the plasma transition (sheath) will be of special interest.

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