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Abstract. A CW 13.56 MHz radiofrequency-driven ion source RADIS for production of H^- and D^- beams is under development for replacing the filament-driven ion source of the MCC30/15 cyclotron. The RF ion source has a 16-pole multicusp plasma chamber, an electromagnet-based magnetic filter and an external planar spiral RF antenna behind an AlN window. The extraction is a 5-electrode system with an adjustable puller electrode voltage for optimizing the beam formation, a water-cooled electron dump electrode and an accelerating einzel lens. At 2650 W of RF power, the source produces 1 mA of H^- (2.6 mA/cm^2), which is the intensity needed at injection for production of 200 µA H^+ with the filament-driven ion source. A simple pepperpot device has been developed for characterizing the beam emittance. Plans for improving the power efficiency with the use of a new permanent magnet front plate is discussed.

Keywords: negative ion source, cyclotron, radiofrequency
PACS: 29.25.Ni, 29.20.D-, 41.75.Cn, 52.50.Qt

INTRODUCTION

A new MCC30/15 cyclotron developed at D. V. Efremov Institute, St. Petersburg, Russia, has been commissioned at the University of Jyväskylä accelerator laboratory (JYFL). The device produces up to 200 µA of 18–30 MeV H^+ and up to 60 µA of 9–15 MeV D^+ from negative ions with high-efficiency stripping extraction. The beams will be used for medical isotope production and nuclear physics experiments at the IGISOL facility. The filament-driven ion source currently used for the production of the injected H^- and D^- beams is limited to about 130 h continuous operation between filament changes when high beam intensity is needed. The ion source is located in the cyclotron vault and therefore a significant waiting time for the vault cooldown is required before filament change is possible. This kind of operation is not acceptable as 350 h and longer experiments are expected once the facility is fully operational. A CW 13.56 MHz radiofrequency-driven ion source RADIS [1] for production of H^- and D^- beams is under development for replacing the filament-driven source. The goal of the RADIS project is to develop a new ion source to produce at least 1 mA of CW H^- beam or 500 µA of CW D^- beam at the cyclotron injection energy of 19 keV, with a maintenance interval of at least one month.

RADIOFREQUENCY ION SOURCE

The ion source design chosen for the RADIS is a multicusp chamber with an external planar spiral RF antenna behind a flat AlN RF window on the back of the ion source. A similar approach has been studied for production H^- [2] and H^+ [3] with promising results. The studies were started by using the 310 mm long multicusp chamber and extraction of the TRIUMF-type H^- ion source LIISA [4]. The ion source filament back plate was replaced with a RF back plate for the testing the RF and the spiral antenna. The water-cooled flat RF antenna of the source is made from 6.35 mm diameter copper tubing and the antenna rounds are insulated from each other with 0.2 mm thick shrink tubing. The 5 kW CW RF power supply is coupled to the antenna using a capacitive T network matching circuit. The RF power supply, matching network and the antenna are all at high voltage. The best result with the test source was 240 µA of H^- and 21 mA of electrons at 1500 W RF input (307 W reflected) [1].

Based on the experience with the test setup a new 127 mm long aluminum Modified MultiPole Structure (MMPS) [5] multicusp chamber, compatible with the existing RF back plate was built for RADIS. The MMPS configuration of the chamber uses magnetic SAE 430 stainless steel strips to redirect the magnetic flux at the poles. The dominant plasma

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losses are at the magnetic poles and therefore the heat flow to the permanent magnets is smaller in MMPS compared to a conventional multicusp configuration, where magnets are located at the poles. The magnetic configuration has 16 rows of SmCo 26 MGOe magnets. Both the magnets and the steel strips are immersed in cooling water. The B-field on the chamber surface is 340 mT at the poles and 290 mT between the poles. The chamber is connected to a plasma electrode with an embedded adjustable electromagnet electron filter similar to one used in the PELLIS ion source [1]. The electron filter field has a maximum peak field of 65 mT and full-width at half-maximum (FWHM) of 20 mm (the on-axis field is presented later in figure 8). The front plate is electrically isolated from the plasma chamber to enable plasma electrode biasing. The plasma electrode aperture is on a removable magnetic stainless steel plasma electrode insert to make possible the use of different aperture sizes. The results shown in this paper are produced using a 7 mm diameter aperture. See figure 1 for a cross-sectional view of the ion source.

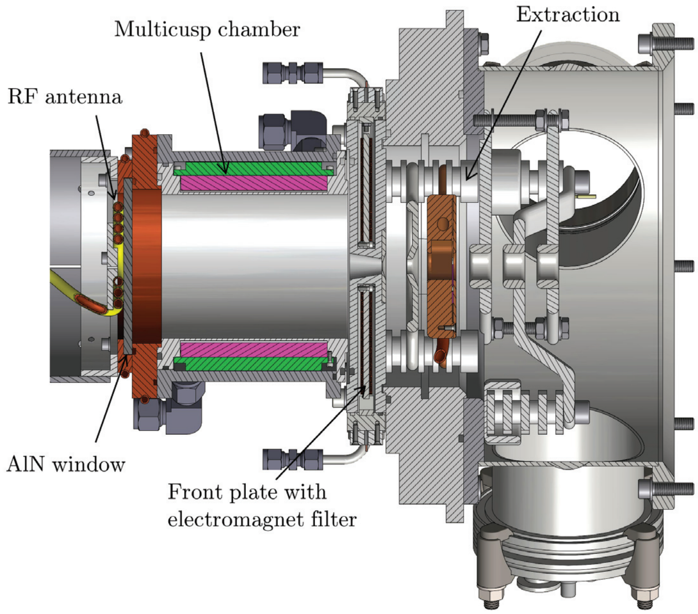

FIGURE 1. Cross-sectional view of the ion source.

The extraction was designed with IBSimu [6] for 1 mA H^- beam and 100 mA of co-extracted electron current. The extraction features an adjustable puller electrode voltage for optimizing the beam formation, a water-cooled electron dump electrode and an accelerating einzel lens. The electron dumping scheme is similar to what has been planned to be used at CERN Linac4 and at Spallation Neutron Source (SNS) [7, 8, 9]. The electron dump has two sets of permanent magnets embedded for producing a field structure, which deflects the co-extracted electrons into the electrode and corrects the slight deflection of the H^- beam passing through the electrode. The electron dump also acts as a decelerating einzel lens. Therefore the beam energy at the dump is relatively low (nominally 6 keV) mitigating the power deposited on the electrode. The electron dump was carefully engineered to be able to handle up to 600 W of heat. The use of accelerating einzel lens at the end of the extraction system enables space charge compensation in the following beam line. See figure 2 for a simulation plot of the extraction system.

A dedicated test-stand was built for RADIS to enable development independent of the laboratory beamtime schedule. The test-stand, shown in figure 3, features a 1000 l/s turbomolecular pump, which provides a base-vacuum of $3 \cdot 10^{-7}$ mbar. The beam current can be measured with a 25 mm diameter aperture Faraday cup (FC1) at 412 mm from the plasma electrode and with a large 160 mm diameter plate (FC2) at the end of the chamber 968 mm from the plasma electrode. The Faraday cups have 150 V electron suppression voltages and there is an additional permanent magnet deflector with 22 mT peak field and 63 mm FWHM on axis at 593 mm from the plasma electrode to ensure that no electrons propagate to FC2. The co-extracted electron current is measured as a current reading of the electron dump electrode high voltage power supply. At 698 mm from the plasma electrode there is a simple pepperpot emittance meter [10], which was built to characterize the beam quality. The pepperpot device has a 0.2 mm thick stainless steel mask with 14×14 array of 0.5 mm diameter holes with 3 mm/hole pitch. A 2 mm thick Vitrosil 077 quartz scintillator screen located 15–100 mm away from the mask is used to produce an image of the beamlets passing through the

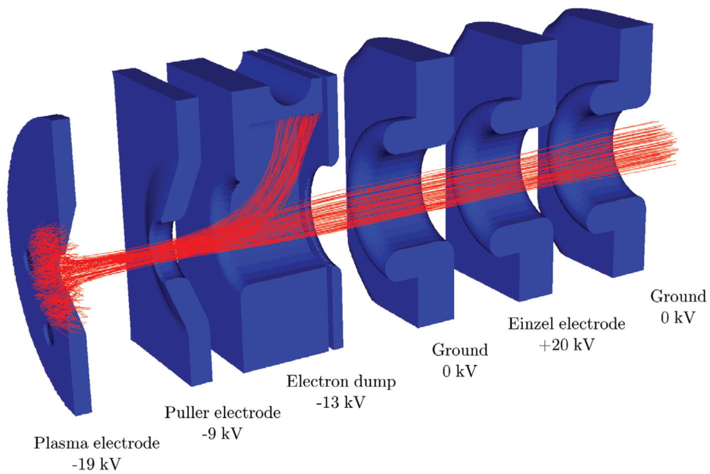

FIGURE 2. Simulation plot of the extraction system transporting 1 mA of H^- beam and dumping 100 mA of co-extracted electrons.

mask holes. The image from the scintillator screen can be photographed from outside the vacuum chamber using a two-mirror system.

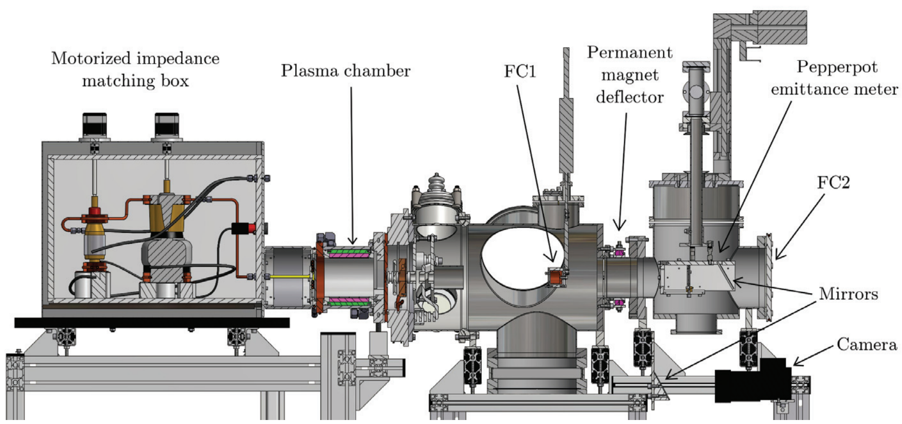

FIGURE 3. Cross-sectional view of the test stand.

EXPERIMENTAL RESULTS

The H^- ion current produced by the ion source as a function of the RF power is shown in figure 4. At best the source has produced 1005 µA of H^- current into FC1 with 2650 W of RF input power (59 W reflected). The plasma electrode bias in this measurement was 28 V and the current was 7.5 A. The filter electromagnet current was 6.2 A, corresponding to 26 mT peak field. The amount of co-extracted electrons was 14 mA. The average electron to ion beam ratio in experiments has been 21 with a standard deviation of ±10. This is only about one fifth of the electron to ion ratio of 100, which was used for designing the beam extraction. This difference may cause a need for readjustment of the plasma electrode to puller electrode distance to achieve optimal beam formation. The ion optics of the beam formation will be studied with systematic emittance measurements as a function of RF power and plasma electrode to puller electrode voltage. The amount of measured co-extracted electrons as a function of measured ion current for recent measurements is shown in figure 5.

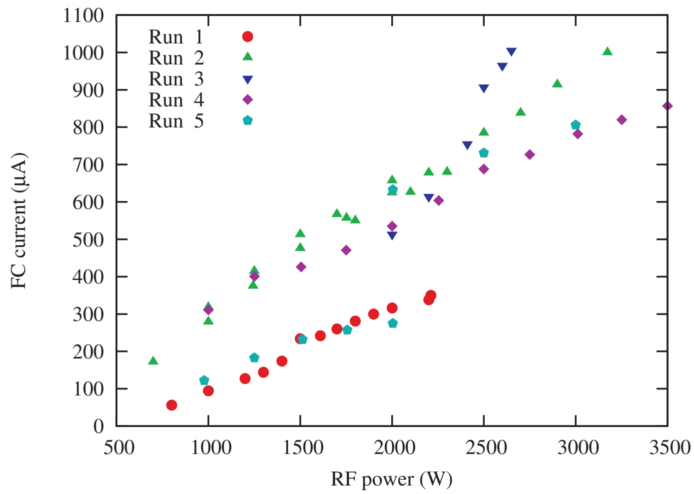

FIGURE 4. Ion current measured at FC1 as a function of RF power for different runs. With optimal ion source tuning a 1 mA/3 kW power efficiency is achieved. In some cases, e.g. runs 1 and 5, the tuning has not been optimal.

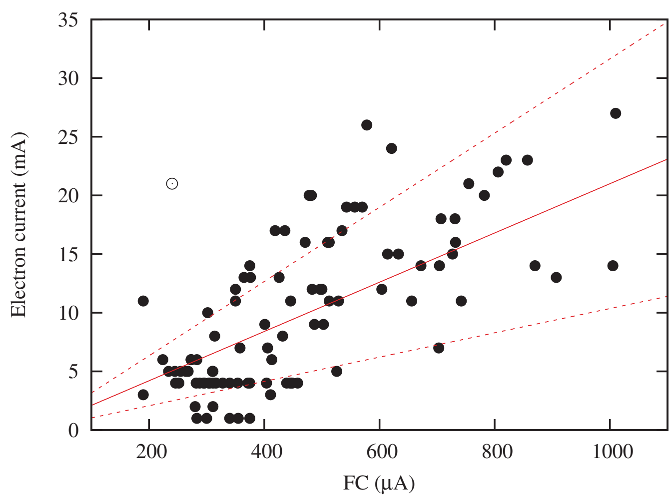

FIGURE 5. The amount of measured co-extracted electrons as a function of measured ion current for recent log-book entries. The fitted solid line represents the average electron to ion ratio of 21 and the area between the dashed lines represents the standard deviation of the entries, which is ±10. The open circle represents the typical values for the initial work with the LIISA ion source.

The pepperpot emittance meter has been used for initial measurements of the beam quality. In these measurements a neutral beam component has been observed in addition to the H^- beam. This neutral beam is insensitive to the einzel lens setting and therefore it is concluded that the neutral beam mostly originates from the first centimeters of the extraction, where the neutral gas pressure is highest. When the pepperpot scintillator images were analyzed, it was observed that due to the relatively large 0.5 mm diameter mask hole sizes the divergence resolution is very limited below 3 mrad. Also the existence of the neutral beam and the intense light from the plasma make the pepperpot image analysis challenging. The best estimate of emittance for a 300 µA H^- beam is $\epsilon_{n,rms} = 0.17 \pm 0.06$ mm mrad and $\epsilon_{n,rms} = 0.19 \pm 0.06$ mm mrad for a 590 µA beam (see figure 6 for the phase space plot). The emittance number is much higher than expected. This might be due to problems in the pepperpot device itself, or due to unforseen behaviour of the beam in the extraction. More work with the pepperpot device is therefore needed. First, the mask needs to be replaced with a one with smaller apertures and verification is needed to ensure that the pepperpot device yields reliable beam quality estimates. A benchmark measurement with a known high-quality beam is planned. If the unexpectedly large emittance beam from the RADIS source persists and the accuracy of the measurements is improved the pepperpot device can be used to find the possible problem in the extraction with systematic studies.

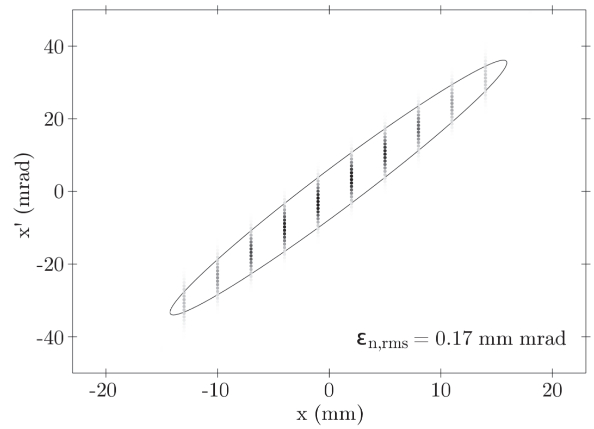

FIGURE 6. Measured emittance of a 300 μA H^- beam.

Recently it was also observed that the extraction alignment was out of place. After investigation it was concluded that the most probable explanation is movement of the einzel electrode, which is bolted to threads on a MACOR insulator. It is possible that tension exceeding the holding force of the bolt is formed in the electrode due to heat expansion leading to movement at the mounting point. More engineering work is needed to solve this issue. The emittance value given above was measured when the extraction was well aligned.

FUTURE PLANS

The goal of the RADIS project is still to be met. The ion source should be able to produce over 1 mA of H^- current persistently. To meet this goal we aim to improve the power efficiency of the ion source by changing the electromagnet (EM) front plate with a permanent magnet (PM) one. Three operational parameters are normally used to tune the cold plasma region where H^- ions are formed: the filter field, the plasma electode bias and the gas pressure. Adjusting these parameters has an effect on the electron to ion ratio and the H^- current. Because of the insensitivity of the ion current to small (±5 mT) changes in the filter field, it is believed that a sufficient optimization can be achieved even with a fixed filter field. The new front plate will be more open near the extraction aperture, which allows more ro-vibrationally excited molecules to flow to the region near the extraction to improve the volume production of H^-. Also because the biased plasma electrode is well separated from the main plasma by the filter field in the new front plate geometry, it will be possible to adjust the local plasma potential near the extraction as in the TRIUMF-type H^- sources [11]. In the current design adjustment of the front plate bias affects the whole plasma potential, which is seen as an affect on the arc voltage/current characteristics when the RADIS chamber was tested with a filament back plate.

The peak field of the new filter was selected to be 27 mT by using the statistics from recent log-book entries shown in figure 7. Most of the log-book entries are written for parameters optimized for maximum H^- current. Therefore the most common peak filter field is a good choice at least for the field topology and source geometry of the EM front plate. The peak field intensity can be adjusted from 20 to 40 mT by changing the magnet-to-magnet distance. The field topology of the PM filter is quite different from the EM filter field. The field has a strong transverse component off axis mitigating plasma losses to the front plate. On axis the field reaches peak value 13 mm before the plasma electrode. Also the integrated field value from the center of the chamber to the biased plasma electrode is much higher in the case of the new PM front plate. See figure 8 for a plot of the transverse filter field of the PM filter and the EM filter on axis and figure 9 for a presentation of the PM filter field topology. A CAD image of the new PM front plate design is shown in figure 10.

After tests with the new front plate and characterization of the beam quality as a function of beam current and plasma electrode to puller electrode voltage have been done, a long term durability test will be done. Also the effect of plasma

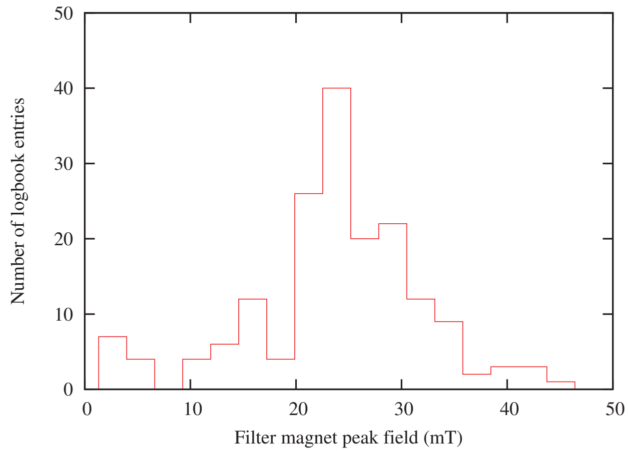

FIGURE 7. A histogram of electron filter field peak values corresponding to EM filter field operation points from recent log-book entries. The statistics is used to select the filter field strength for the PM front plate.

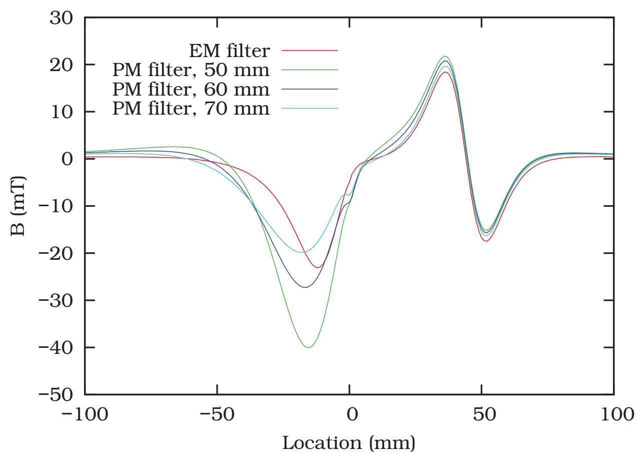

FIGURE 8. Transverse magnetic field on the z-axis for the current EM filter with 23 mT peak field (most typical operation point) and the field of the designed PM filter with three different magnet to magnet distances. The negative z-values are inside the plasma chamber and the positive z-values in the extraction. The EM orientation differs from the electron dump orientation by 30 degrees. Therefore in the plot, the transverse field direction differs for $z < 0$ for the EM case.

electrode aperture to the emittance and beam current will be analyzed to optimize the performance at the MCC30/15 cyclotron. Before the ion source is installed at the cyclotron, the existing injection line will require modification to adapt to the different phase space properties of the beam originating from the RADIS ion source compared to the original ion source.

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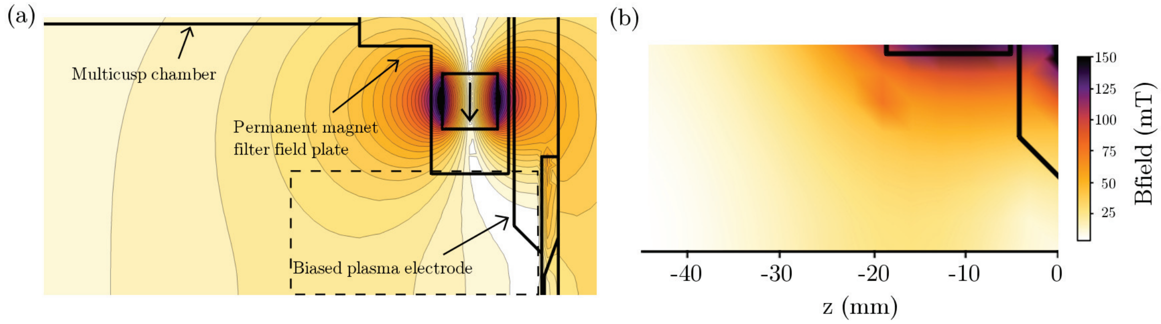

FIGURE 9. The PM filter field: (a) A contour plot of the magnetic vector potential of the PM filter field. The contour lines are equal to B-field lines. The geometry of the ion source is overlaid to illustrate the location of the permanent magnets. (b) Magnitude of the magnetic field in the region surroinded with dashed line in the figure a. The field calculation does not include the plasma chamber multipole magnets.

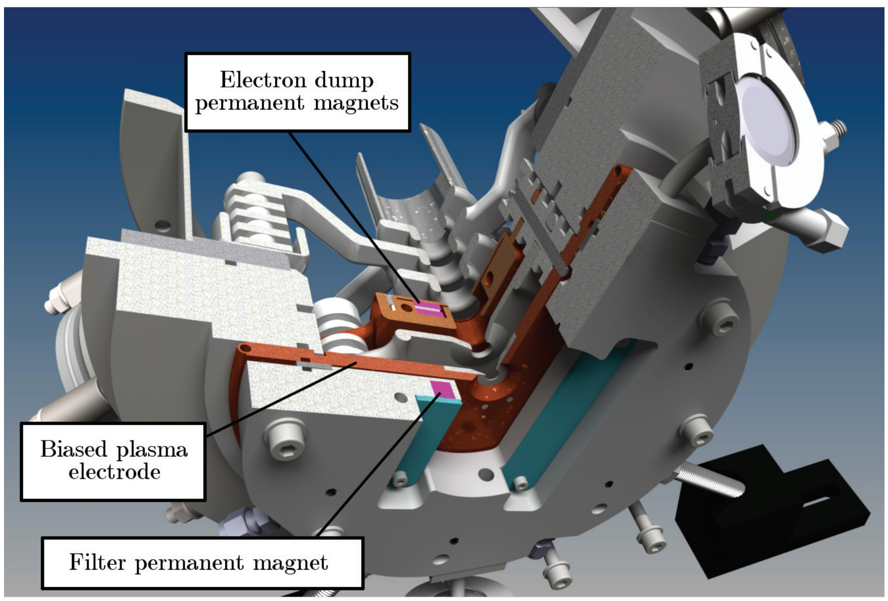

FIGURE 10. A CAD rendering of the new PM filter front plate.

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