INITIAL TESTS OF THE SNS H^- ION SOURCE WITH AN EXTERNAL ANTENNA

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Abstract

The ion source for the Spallation Neutron Source* (SNS) is a radio-frequency, multicusp source designed to deliver H^- beam pulses of 40 mA to the SNS accelerator with a normalized, RMS emittance of less than 0.2 π mm mrad, with a pulse length of 1 ms and a repetition rate of 60 Hz. In order to achieve this performance the source must operate with both high pulse RF power, ~50 kW, and high average RF power, ~3.5 kW, over a continuous operational period of 3 weeks. During operation at these power levels the plasma-immersed, porcelain-coated RF antenna is susceptible to damage, limiting source lifetime. We are therefore developing an ion source where the plasma is separated from the Cu antenna by an Al_2O_3 discharge chamber. This report describes the ion source, presents initial beam extraction measurements and details our ongoing effort to develop this concept into a suitable ion source for the SNS.

* SNS is a collaboration of six US National Laboratories: Argonne National Laboratory (ANL), Brookhaven National Laboratory (BNL), Thomas Jefferson National Accelerator Facility (TJNAF), Los Alamos National Laboratory (LANL), Lawrence Berkeley National Laboratory (LBNL), and Oak Ridge National Laboratory (ORNL). SNS is managed by UT-Battelle, LLC, under contract DE-AC05-00OR22725 for the U.S. Department of Energy.

I. INTRODUCTION

High-brightness H^- ion sources are widely used in large accelerator facilities which utilize charge-exchange injection into circular accelerators or storage rings. Several new facilities, currently in the planning, construction or commissioning stages, will be required to deliver considerably more beam power to targets than is currently available at today's facilities [1,2]. One such facility, the US Spallation Neutron Source (SNS)* employs a Radio-Frequency (RF), multicusp ion source designed to deliver H^- beam pulses of 40 mA to the SNS accelerator with a normalized RMS emittance of less than 0.2 π mm mrad, with a pulse length of 1 ms and a repetition rate of 60 Hz [3, 4]. In order to achieve this performance the source must operate with both high pulse RF power: ~50 kW, and high average RF power: ~3.5 kW, over an operational period of 3 weeks. During continuous operation at these power levels the plasma-immersed, porcelain coated RF antenna is susceptible to damage, limiting source lifetime.

Although recent advances in antenna coating technology [5] have resulted in substantial performance improvements [6, 7] it is doubtful that internal antennas can ever be truly competitive with external antenna systems which couple RF power into the plasma through a thick dielectric plasma chamber wall [8]. The DESY group was the first to apply this concept to the field of H^- generation by employing an aluminum oxide cylinder to separate the plasma from the RF-antenna [9]. Operating at comparable RF pulse powers to the SNS requirement but at less average RF power (pulse width:100-200 us; repetition rate: 6 Hz) the system has demonstrated over 25,000 hours of maintenance-free operation. Based on this success, we are currently developing an SNS version of the DESY source. The first beam measurements are presented as well as a discussion of the development effort required to implement this concept on the SNS accelerator.

II. THE ION SOURCE

Figure 1 shows a cross sectional view of the ion source. It consists of the original SNS ion source produced by Lawrence Berkeley National Laboratory (LBNL) [4] combined with a reentrant external antenna module designed at ORNL [10]. The plasma is confined by a multicusp magnet field created by a total of 20 samarium-cobalt magnets lining the cylindrical chamber (ϕ=10 cm, l=10 cm) wall and 4 magnets lining the back plate. A magnetic dipole (150-300 Gauss) filter separates the main plasma from a smaller H^- production region where low-energy electrons facilitate the production of negative ions. An air cooled/heated collar surrounding this H^- production volume dispenses small quantities of Cs, which greatly enhances H^- production. Once the negative ions are extracted a 0.16 T transverse magnetic field dumps the co-extracted electron beam on a dedicated dumping electrode, maintained with a ~5 kV positive bias with respect to the extraction aperture.

The external antenna module, shown in Fig. 2, contains a high-purity Al_2O_3 plasma chamber (ϕ=4.8 cm, l=10 cm and Δt=0.6 cm) secured by the compression of two o-rings. A 6-turn helical water-cooled antenna constructed from uncoated copper tubing (ϕ=5 mm) surrounds the plasma chamber. The straight portion of the antenna is shielded from arcing by two ridged Al_2O_3 tubes and the curved portion of the antenna is shielded radially from the outer wall by 2 layers of flexible 3 mm Teflon sheet. The antenna cavity is cooled by flowing air or water through opposing inlet and outlet ports which penetrate the back-flange. Beam-pulses are produced with the application of power from a pulsed 2 MHz (P=80kW max) RF generator and plasma is maintained between beam-pulses by the continuous application of 13.56 MHz (P=600W max). Each RF supply is connected to the antenna through individual matching networks which are designed to maintain a high degree of RF isolation between supplies.

III. BEAM EXTRACTION MEASUREMENTS

The source was tested on the SNS ion source test stand, which consists of an ion source, a Low Energy Beam Transport (LEBT) section consisting of two Einzel lenses, a toroidal Beam Current Monitor (BCM) and a water-cooled faraday cup [11]. Initial attempts to ignite plasma using the 13.56 MHz generator were unsuccessful due to an impedance mismatch created by the much higher impedance of the 6-turn external antenna compared with the original 2.5-turn internal antenna. After designing and implementing a new 13.56 MHz matching network, we found the plasma could be routinely ignited with the application of P > 400 W and a burst of H_2 gas flow: 100 SCCM for 1 s. Stable plasma could be maintained for P = 250-600 W with only a few percent of the power reflected.

The application of 2 MHz RF power to the external antenna had a destabilizing effect on the plasma causing it to extinguish with increasing RF pulse length and RF power and with decreasing H_2 gas flow rate. Fig. 3 shows the maximum 2 MHz pulse length and maximum power-level under which the source could run in a stable mode as a function of H_2 flow-rate. Above these maximum values the plasma would extinguish and require manual re-ignition. This behavior contrasts sharply with the internal antenna which operates in stable mode over a much wider parameter range; H_2 flow: 30-50 SCCM; Pulse width: 50-1200 μs; RF power: 10-60 kW.

Fig. 4 shows the dependence of the extracted H^- beam current on applied 2 MHz RF power. Note: as discussed above, H_2 flow rates were increased with increasing power in order to prevent the plasma from extinguishing. The H^- beam current was about 20% higher than typically measured from a un-cesiated SNS ion source employing an internal antenna. We attempted to cesiate the ion source by interrupting cooling air flow to the collar and running the plasma at the highest achievable duty-factor: P_{13MHz} = 600W; P_{2MHz} = 50 kW; pulse width = 100 us; rep. rate = 60 Hz. Under these conditions the Cs collar only reached 300 C, which is well below the temperature for Cs release [6].

Previous analysis has shown that simply flowing water through the antenna cavity would be a straightforward approach to meeting the cooling requirement of the source during operation at the full SNS beam power requirement [10]. In order to determine the effect of this cooling scheme on the extracted H^- beam current the air cooling lines were replaced with a ~2gal/min flow of de-ionized water. Measures were taken to insure the antenna cavity was free of air pockets. Stable plasma was readily formed and the extracted beam current was observed as a function of applied RF power. This data is plotted in Fig. 5 and shows water cooling the antenna cavity reduced the beam current by ~50%.

To aid in computational investigations of alternative cooling schemes, measurements of the plasma heat flux were undertaken. A simple stainless steel rod of known dimension and material quality was inserted in place of the view port located on the back-flange of the source. The rod contained two hollow channels to hold thermocouples at different depths separated by a known thermal resistance. The closed end of the rod was directed at the plasma center and the curved surface of the rod was shielded from plasma bombardment by the view port walls. The flat end of the rod was directly heated by plasma bombardment and the difference in the two measured temperatures was used to calculate the incident heat flux. The heat flux was found to vary linearly with RF power, pulse width and repetition rate allowing straightforward scaling to the full SNS beam requirement (1.2 ms, 60 Hz, ~50 kW of RF power). A heat flux of 47 kW/m^2 at the full operational requirement of the SNS was determined from these data.

IV. DISCUSSION

The observation of the large H^- beam current obtained with the ion source in a completely uncesiated state is very encouraging since adding Cs typically increases the beam current by a factor of 2-3 when using the internal antenna [6]. This beam current exceeds that extracted from any other uncesiated H^- ion source tested in our laboratory. This effect is most likely a consequence of using the higher inductance of the 6-turn antenna versus the conventional 2.5-turn internal antenna. The 6-turn antenna likely leads to stronger inductive RF coupling to the plasma resulting in higher plasma densities. Since the external antenna employs a thick walled Al_2O_3 chamber isolating the antenna from the plasma, capacitive coupling through the RF electric fields of the antenna is clearly reduced. This effect is likely related to our difficulty maintaining stable plasma for long RF pulses and at low H_2 gas flow rates.

In order to improve plasma stability to support longer pulses and lower gas flow-rates we have designed and fabricated a small ignition chamber capable of injecting a steady-state plasma stream into the source [12]. Following the approach taken by DESY [13] this chamber is affixed to the back-flange of the ion source and serves as the point-of-entry for the H_2 feed-gas. A 2 mm aperture restricts gas flowing from the ignition chamber to the ion source creating higher pressure in the ignition chamber. The system is designed so that the pressure in the ignition chamber is high enough to support a continuous Paschen discharge created by the application of a few hundred volts across a small gap located in that chamber. The geometry is such that electrons from this discharge will stream continuously into the main ion source plasma chamber stabilizing the primary RF plasma. This approach has been applied successfully in the DESY system; stabilizing the plasma allowing low H_2-flow rates and 2 MHz pulses of length ~200 μs (RF power supply limit). This system is ready and will be tested shortly after this conference.

This investigation has shown that the plasma chamber cooling scheme envisioned in Ref. 10, based on water cooling the antenna cavity, will seriously reduce the extracted H^- beam current. Applying the measured heat load of 47 kW/m^2 to a thermal model of the ion source [10] also suggests that simple air cooling of the antenna cavity will be insufficient to prevent o-rings failure. We are therefore currently redesigning the plasma chamber configuration to accommodate partial water cooling circuits based on the information which has become available during this investigation.

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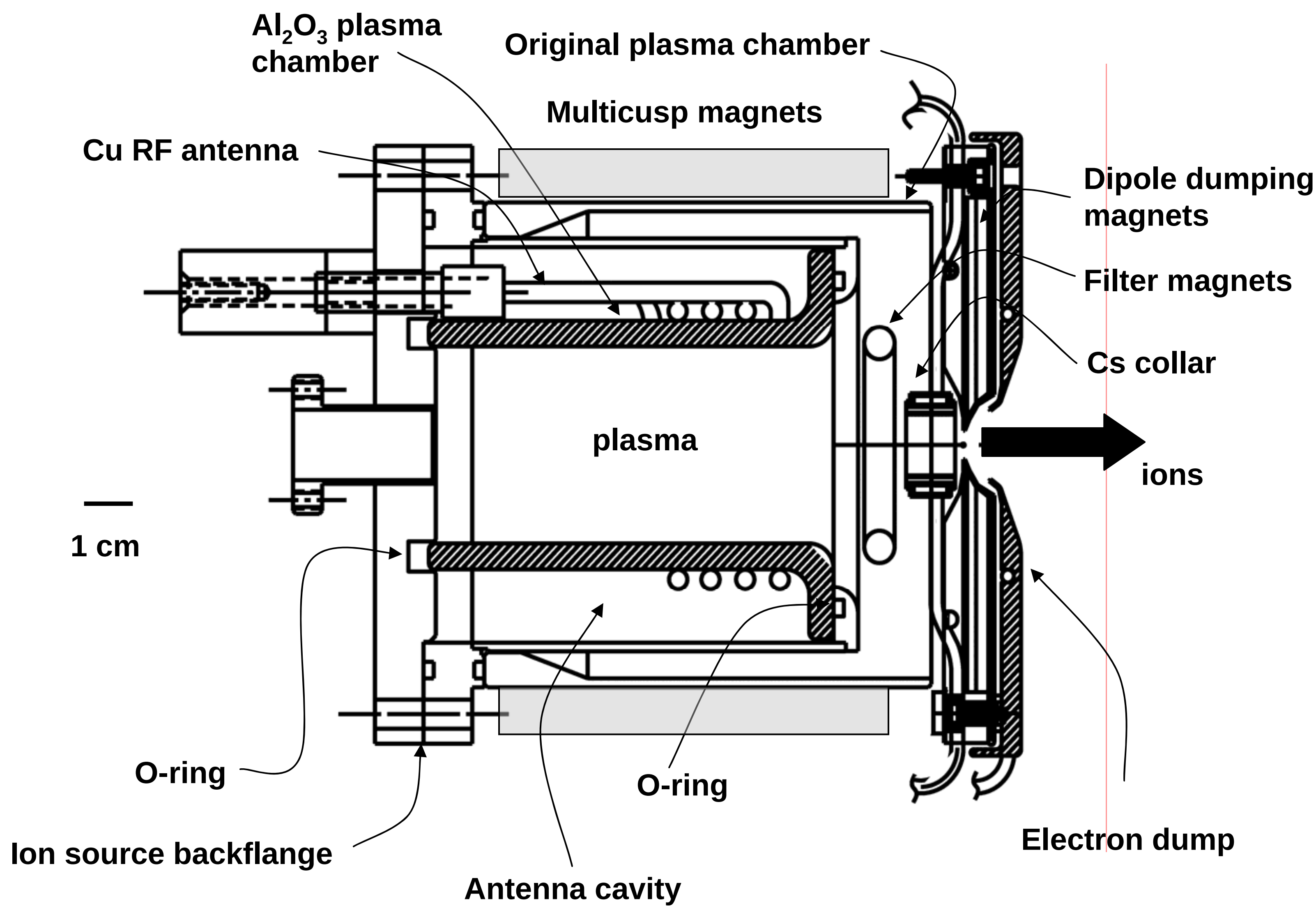
Figure 1. A cross-sectional view of the SNS ion source employing the external antenna.

Figure 2. A cut-out view of the reentrant external antenna module which replaces the back-flange in the original LBNL ion source.

Figure 3. (a) Maximum 2MHz RF power which could be applied to the antenna without extinguishing the plasma (pulse length=100 μs; 13.56 MHz power=600W). (b) Maximum 2MHz RF pulse length which could be applied to the antenna without extinguishing the plasma (2MHz power=30 kW; 13.56 MHz power=600W).

Figure 4. Extracted H^- beam current as a function of 2MHz RF power. Note the H_2 flow rate has been increased with increasing power to maintain the plasma (see text).

Figure 5. Extracted H^- beam current versus 2MHz power for the antenna cavity cooled with air (circles) and cooled with water (diamonds).



Al2O3 plasma chamber
Original plasma chamber
Multicusp magnets
Cu RF antenna
Dipole dumping magnets
Filter magnets
Cs collar
plasma
ions
1 cm
O-ring
Ion source backflange
Antenna cavity
O-ring
Electron dump

Figure 1

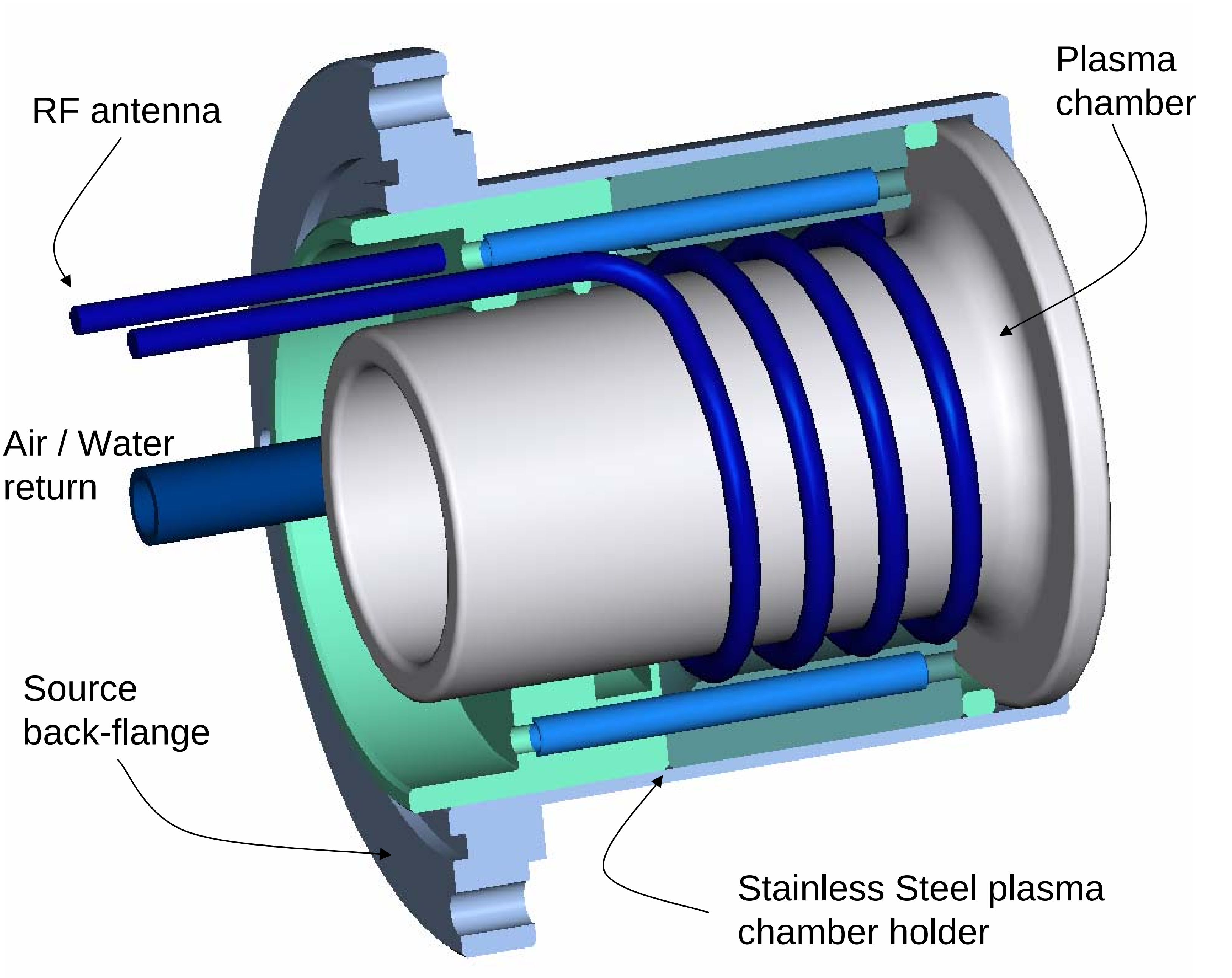
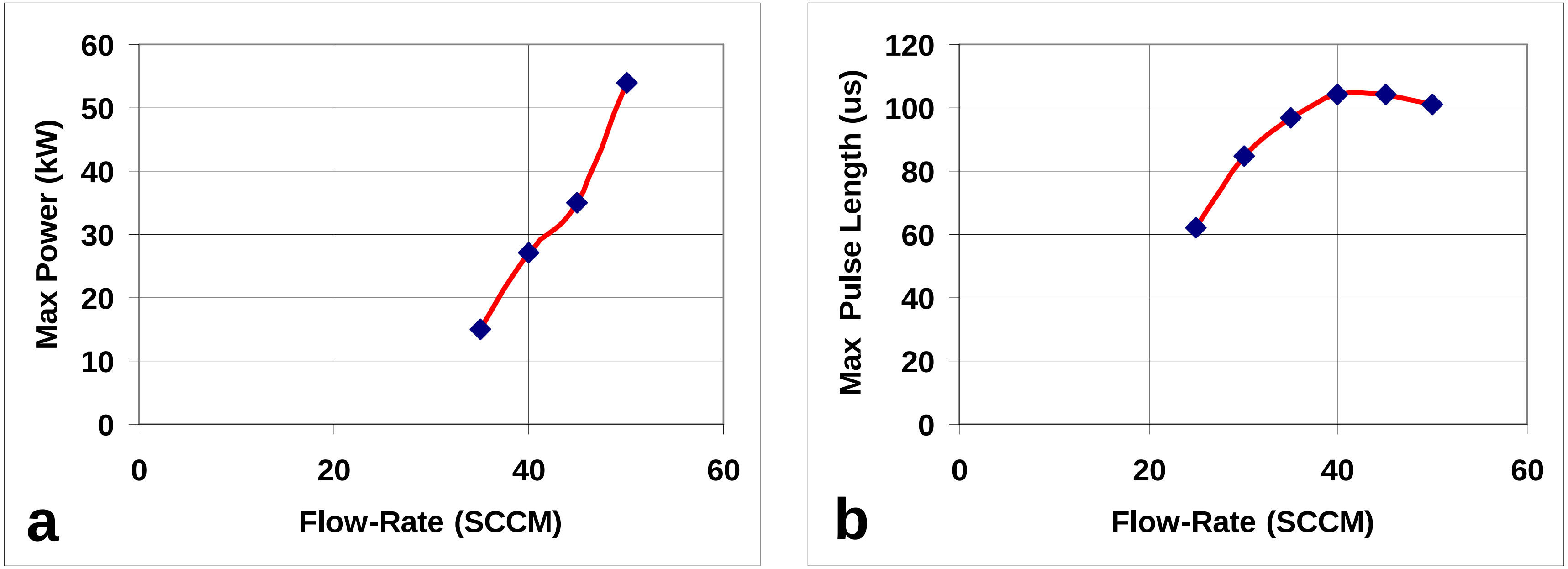

Plasma
chamber
RF antenna
Air / Water
return
Source
back-flange
Stainless Steel plasma
chamber holder

Figure 2



60
50
40
30
20
10
0
Max Power (kW)
0
20
40
60
a
Flow-Rate (SCCM)
120
100
80
60
40
20
0
Max Pulse Length (us)
0
20
40
60
b
Flow-Rate (SCCM)

Figure 3

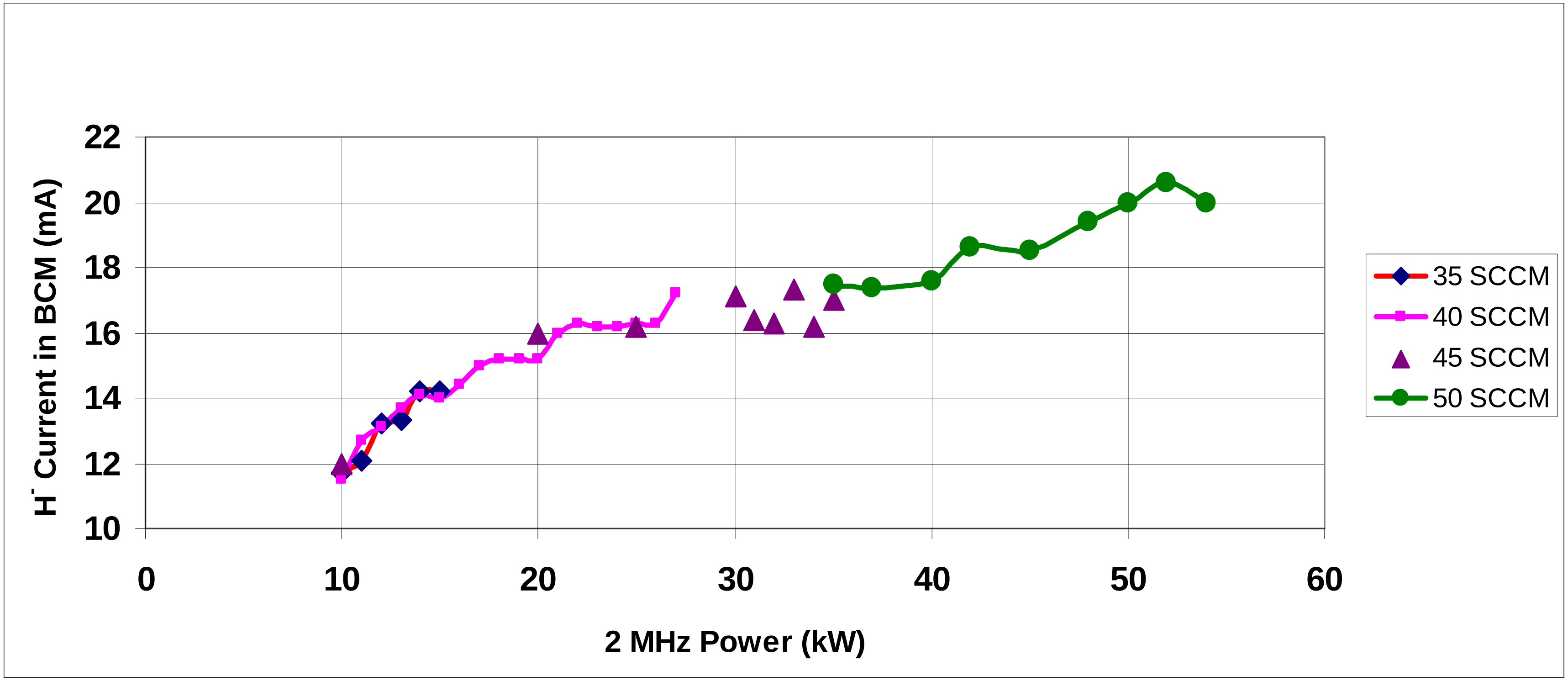
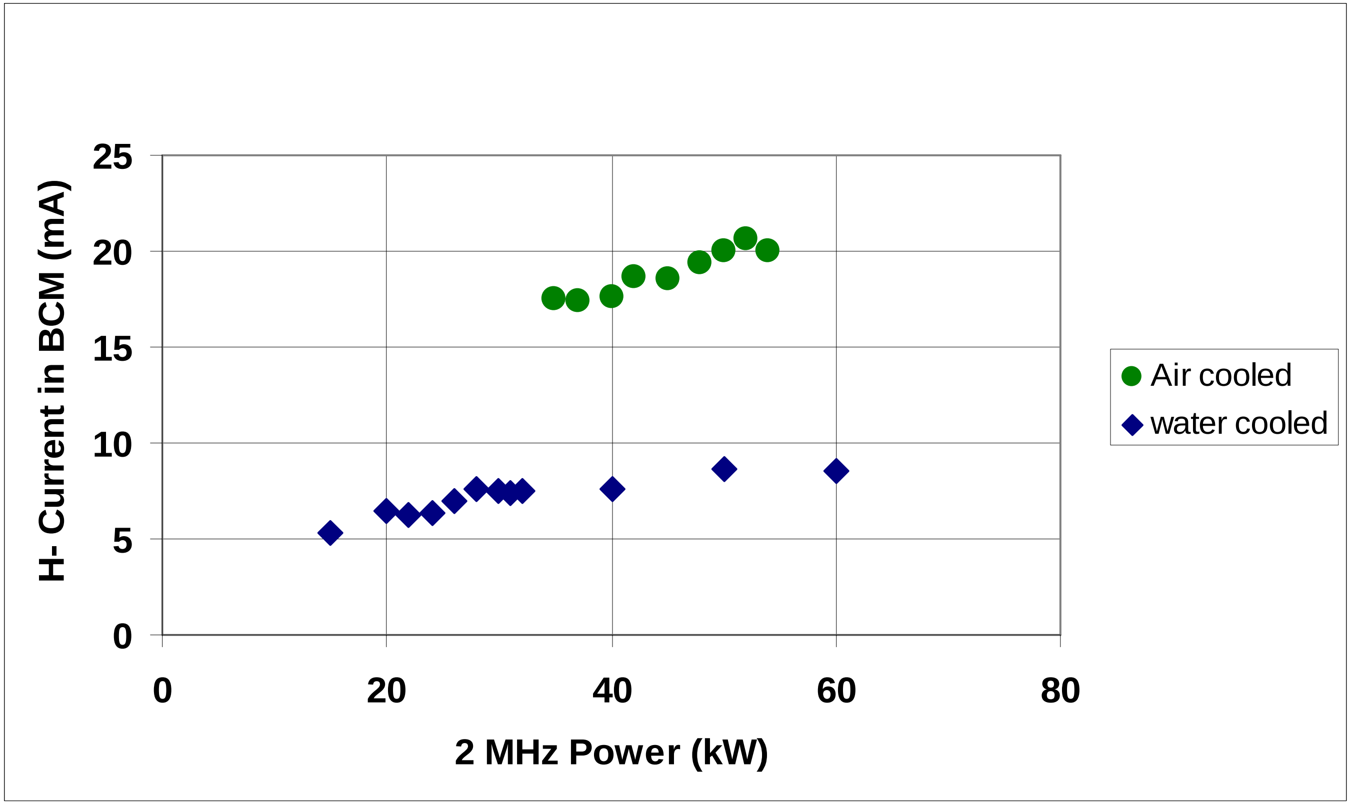

22
20
18
16
14
12
10
H- Current in BCM (mA)
0
10
20
30
40
50
60
2 MHz Power (kW)
35 SCCM
40 SCCM
45 SCCM
50 SCCM

Figure 4



25
20
15
10
5
0
H- Current in BCM (mA)
0
20
40
60
80
2 MHz Power (kW)
Air cooled
water cooled

Figure 5