

Plasma ignition schemes for the SNS radio-frequency driven H^- source

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The H^- ion source for the Spallation Neutron Source (SNS) is a cesiated, radio-frequency driven (2 MHz) multicusp volume source which operates at a duty cycle of 6% (1 ms pulses and 60 Hz). In pulsed RF driven plasma sources, ignition of the plasma affects the stability of source operation and the antenna lifetime. We are reporting on investigations of different ignition schemes, based on secondary electron generation in the plasma chamber by UV light, a hot filament, a low power RF plasma (cw, 13.56 MHz), as well as source operation solely with the high power (40 kW) 2 MHz RF. We find that the dual frequency, single antenna scheme is most attractive for the operating conditions of the SNS H^- source.

1. Introduction

The H^- ion source for the Spallation Neutron Source (SNS) [1] is a multicusp source in which the hydrogen plasma is sustained by 2-MHz radio frequency power of up to 50 kW inductively coupled through a metallic, insulator-covered antenna. [2-5]. The source is operated at a duty cycle of 6%, with 1 ms long pulses at a repetition rate of 60 Hz. Since the 2 MHz plasma is pulsed the issue of plasma ignition arises. Ignition typically is not a problem in multicusp sources, in which a discharge is sustained through

thermionic electron emission from a set of filaments. The ignition of the pulsed plasma requires the delivery of a given number of free electrons into the plasma chamber at the beginning of the pulsed RF. These electrons can then be accelerated in the alternating electrical and magnetic fields generated by the antenna, and lead to an avalanche of ionizations and the formation of a plasma for the duration of the 2 MHz pulse. We have investigated four basic ignition schemes, the merits and drawbacks of which we will discuss after a brief description of the experimental setup. It should be noted here that these studies are aimed at the construction of a highly reliable production machine that is designed to operate for about 500 h continuously after brief maintenance periods.

2. Experimental setup

In Figure 1 we show a schematic of the RF driven multicusp source. Details of the SNS ion source have previously been published [2-5]. Briefly, the source utilizes the volume-type of H^- production, assisted by trace amounts of cesium deposited on the inside of a small second chamber. Vibrationally excited H_2 molecules are formed in the plasma region around the antenna and diffuse through the filter magnet field into the H^- production region from where the beam is extracted. Here, they can undergo dissociative attachment, forming the desired H^- in a volume production process. The surfaces of the extraction region are coated with Cs so as to also take advantage of surface conversion processes for H^- formation. The RF antenna consists of a water cooled copper tube with 2- turns [change to hyphen] and a thin dielectric coating. Since the antenna is exposed to energetic ions, neutrals, electrons, and photons in the high power plasma, its lifetime is of great concern [6]. The two ports in the back plate of the ion source can be used to supply

the hydrogen gas, to mount a UV transmitting quartz window for plasma ignition and / or optical spectroscopy, and for the mounting of a filament for ignition support.

3. Results

3.1. Self-ignition

For a wide range of operational conditions, coupling of RF power into an ion source leads directly to plasma ignition. In cw operation, the ignition often requires a transient increase of the working gas pressure. Once the plasma is ignited, it can be sustained at much lower gas pressures. In a pulsed source this would require either a modulation of the gas pressure or a memory effect where ignition for the $(n+1)^{\text{th}}$ RF pulse is aided by remnants of the n^{th} pulse. Once started, we found that a pulsed plasma can be sustained, but the working pressure was generally too high and could not be varied enough to optimize H⁺ production. Also, the necessary conditions for self-ignition (H₂ pressure, RF power) change during the source conditioning process. The H₂ working pressure of choice is in the range of 10 to 25 mTorr. We found that the memory effect is not strong enough to resolve the ignition issue at a duty cycle of 6%. Gas modulation at the operating frequency of 60 Hz was not pursued.

3.2. Thermionic electron emission from a filament

Continuous ohmic (~15 A at 10V) heating of a thin (~ 0.5-mm diameter) tungsten wire in vacuum readily provides electrons from thermionic emission. The filament can be brought into the plasma chamber through a port on the back plate, and the length of the filament wire can be adjusted so as to supply electrons close to the antenna where

they can be accelerated by the pulsed RF. Filamentbased thermionic emission is rather straightforward and works very well (see Figure 3 below) [Figure 3 is mentioned before figure 2?] but can't be used for our purposes. The reason does not lie in the limited filament lifetime, which could be optimized by proper choice of filament diameter and operating current. The main drawback is the unavoidable metallic coating of the antenna that accompanies prolonged filament operation. This coating was found to result in severe instabilities in source operation after a few days, necessitating premature antenna replacement.

3.3. Photoemission

Photoemission is an attractive approach to the starting of a pulsed RF driven plasma in a multicusp source [5]. Pickard et al. demonstrated this scheme with a 20 mJ xenon flash lamp and utilizing photoemission from copper surfaces inside the plasma chamber. Pulses from a UV flash lamp are synchronized with the starting flank of the pulsed 2 MHz RF power, and photoelectrons aid the plasma ignition. UV light was coupled into the plasma chamber through a port with a quartz window in the back plate.

Photoemission from plasma chamber surfaces was chosen since an immersed, dedicated photo cathode would be subject to rapid erosion,, ceasing to function and at the same time releasing unwanted impurities into the source. The plasma chamber body of the SNS source, however, is made of stainless steel, rather than copper to avoid build-up of insulating copper oxide layers. The quantum yield in photoemission depends strongly on the work function of the surface from which electrons are to be released following the adsorption of a photon. We found that photoemission does aid plasma ignition when

using a 5 J Xe flash lamp. This method suffered, however, from poor reproducibility, and the photon production rate was also not intense enough, strongly limiting the H₂ tuning range. Several problems are apparent. First, the surface conditions of the plasma chamber interior are not well defined and change with operation time. Also, the effective photo-cathode areas are not biased, but rather subject to the magnetic fields of the plasma-confining cusps and the fields of filter magnets. We found quantum yields for UV from the Xe flash lamp in the order of 10⁻⁴, but the lack of an extraction bias and the presence of the magnetic fields make it seem plausible that photoemission is inefficient.

Use of a high power UV laser would improve the efficiency, since a favorable electron emission spot can be selected. However, the requirement of the 60 Hz repetition rate is challenging for available N₂ lasers, and their lifetime is also limited to about 10⁷ shots before the discharge cartridge has to be exchanged - an unwanted complication.

3.4. Dual frequency mode

The forth and final path to stable and reliable plasma ignition of the pulsed 2 MHz plasma is a dual frequency mode of operation. The idea for this originated in work with pulsed 13.56 MHz plasma sources where it was found that one RF amplifier could be modulated to provide high power pulses and between them supply low-amplitude RF power that was sufficient to keep a low-density plasma burning continuously[7].

Attempts to implement this scheme with a given 2-MHz high-power amplifier have so far been unsuccessful. But as an extension of this principle, a low-density plasma can be sustained with RF at 13.56 MHz, and this plasma aids the ignition of the high power, pulsed 2 MHz plasma. Under certain conditions, power levels of only a few tens of W

suffice to sustain a cw plasma in the desired H₂ pressure range. In figure 2 we show light emission in the visible part of the spectrum for a pulsed MHz plasma (25 kW) and a cw 13.56-MHz plasma (100 W). A compact, PC based fiber spectrometer [give reference if necessary!] allows collection and quantification of the spectral light emission. For these measurements an optical fiber was placed at the quartz window of one of the ports in the source back plate. Access to quantitative light emission data has been helpful in the optimization of the cw plasma operation. Also, ways to exploit this plasma diagnostics tool for beam parameter optimization, especially in regard of the presence of wanted (e. g. cesium) and unwanted (e. g. oxygen) impurities are being pursued.

In Figure 3 [?] we demonstrate the effectiveness of plasma ignition aid on scope traces of the extracted H⁻ current. The beam current was measured with a biased and magnetically screened, cooled Faraday cup in the position where the LEPT of the SNS ion-source system would be, see Figure 1. The source was not cesiated for these tests, the beam energy was 65 kV, and the average H⁻ current was at the 10 mA level. The 2-MHz RF power was 35 kW, while the cw 13.56-MHz power was only 30 W. When running the source without ignition aid, the onset of the H⁻ current pulse is delayed by 25 μs as compared to the current pulses were an ignition aid was present. The time between RF gate and the ignition-aided current pulse stems from an internal delay of the 2-MHz RF amplifier. The effect of filament and low power cw plasma on the speed of ignition are comparable. A cw RF power of about 20 W is required to sustain the plasma, and any cw plasma was found to aid ignition efficiently. There was no effect on the H⁻ current onset when the cw power was varied from 20 W to 280 W.

In these measurements, both 2 MHz and 13.56 MHz RF power were coupled into the source through a single, quartz-insulated steel antenna. The 13.56 MHz power is fed into the antenna through a separate impedance matcher. We selected a newly developed capacitor-based impedance matcher for the 13.56 MHz circuit [8]. Experiments with a second antenna for 13.56 MHz were aborted since the single antenna scheme offered a more compact solution.

Concerns regarding off-pulse H⁻ current from the cw plasma are unsubstantial since the RF power levels are very low. If there were sufficient current to cause concern, it could also be dumped with help of the existing LEPT beam chopper [4].

Figure 4 displays scope traces of antenna currents for the 2 MHz and 13.56 MHz circuits as measured by Pearson transformers. Figure 4 a) shows that the 13.56 MHz (160 W) induced current of 30 A all but vanishes during the 2 MHz pulse. The latter induces a current of 400 A at a power of 25 kW. The displayed 2 MHz antenna current trace suffers from under sampling and only the envelope is important here. We expand the trailing edge of the pulses in figure 4 b. Clearly visible is the delay between the end of the 2 MHz pulse and the recovery of the 13.56 MHz pulse. This delay usually causes the plasma to extinguish. The measured recovery time was found to be a property of the 13.56 MHz amplifier. The 13.56 MHz matcher impedance is well matched to the low-density, off-pulse plasma. But when the 2 MHz high-power pulse strikes, the 13.56 MHz system is badly mismatched, and essentially all RF power is being reflected back to the amplifier. The protection circuit of the amplifier is now activated and shuts the output of 13.56 MHz RF down. Once the 2 MHz pulse has ended, the 13.56 MHz power is turned back on only with an amplifier-specific delay. We eliminated this hardware problem by

use of a 13.56 MHz amplifier with much higher nominal output, operating it in a way that all reflected RF power could be absorbed without triggering the protection circuit. Proper gating of the power output and/or delaying the response of the protection system for 1 ms are envisaged to be ways of overcoming this instrumentation problem with an amplifier of lower power rating.

4. Conclusion

A single antenna, dual frequency mode of operation that uses low-power cw 13.56 MHz and high-power pulsed 2 MHz has emerged as the mode of choice for operation of the SNS H⁻ source. The critical issue of cw RF recovery following the mismatch conditions during the 2 MHz pulse has been addressed by the choice of a resilient 13.56 MHz amplifier. This mode promises to eliminate detrimental plasma starting effects on antenna lifetime and enables stable and reproducible operation with high reliability in a compact setup.

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References

- [1] B.R. Appleton, J.R. Alonso, J.E. Cleaves, T.A. Gabriel, W.T. Weng, A.J. Jason, R.A. Hardekopf, D.P. Gurd, R.A. Gough, R. Keller, B.S. Brown, R.K. Crawford, "Status

Report on the Spallation Neutron Source (SNS) Project,” EPAC ‘98, Stockholm (1998).

and: www.sns.gov

[2] R. Thoma, R. Gough, R. Keller, M. Leitner, K. Leung, D. Meyer, M. D. Williams, Rev. Sci. Instr. 71, 1213, (2000)

[3] M. A. Leitner, R. A. Gough, K. N. Leung, M. L. Rickard, P. K. Scott, A. B. Wengrow, M. D. Williams, and D. C. Wutte, Rev. Sci. Instr. 69, 962 (1998); K. N. Leung, *ibid.*, 998

[4] R. Keller, et al., these proceedings; R. Keller, Proceedings of the 1999 Particle Accelerator Conference, New York, 1999, P. 87; R. Keller, et al., Proceedings of the 2001 Particle Accelerator Conference, Chicago, 2001 (in press)

[5] D. S. Pickard, K. N. Leung, L. T. Perkins, D. M. Ponce, and A. T. Young, Rev. Sci. Instr. 67, 428 (1996)

[6] R. Welton et al., these proceedings

[7] J. Reijonen, K. N. Leung, unpublished

[8] J. Staples, and T. Schenkel, Proceedings of the 2001 Particle Accelerator Conference, Chicago, 2001 (in press)

Figure 1. Schematic of the SNS H⁻ source [1-4].

Figure 2: Spectra of visible light emitted from the cw 13.56 MHz plasma at an RF power of 100 W (bottom) and from the pulsed 2 MHz plasma at 25 kW (top). The 2 MHz induced emission was attenuated so that the Balmer α line was not saturated. The insert shows the Balmer γ line from the pulsed plasma.

Figure 3. Traces of extracted H⁻ current pulse and RF gate (0.55 ms pulse length) with cw 13.56 MHz power (solid gray, first pulse), with filament on (dashed gray), and without ignition aid (solid black).

Figure 4: a) Traces of the RF pulse gate (0.9 ms, 10 Hz), and antenna currents as measured with Pearson transformers at the 2 MHz matcher during the 25 kW 2 MHz pulse (400 A; gray dashed), and at the 13.56 MHz matcher (30 A, solid black). The cw 13.56 power was 160 W. b) Focus on the trailing end of the pulse shows the delayed recovery of the 13.56 MHz pulse after the decay of the 2 MHz pulse. The bottom trace shows the cw 13.56 MHz antenna current in the absence of a pulsed 2 MHz pulse.









