Linac4 H^- source R&D: Cusp free ICP and Magnetron Discharge

J. Lettry[1, a)], S. Bertolo[1], U. Fantz[2], R. Guida[1], K. Kapusniak[1], F. Di Lorenzo[1], C. Machado[1], C. Mastrostefano[1], T. Minea[3], M. O'Neil[1], H. Neupert[1], D. Noll[1], D. Steyaert[1], N. Thaus[1]

[1]*CERN, 1211 Geneva 23*
[2]*IPP-Garching and Uni. Augsburg.*
[3]*LPGP Orsay.*

a)Corresponding author: Jacques.lettry@cern.ch

Abstract. The 2MHz radio-frequency inductively coupled plasma heating (ICP RF) of Linac4's IS03 H^- source is more efficient without its octupole cusp in offset hallbach configuration. This was shown by Particle in cell Monte-Carlo (PIC-MC) simulation using the NINJA software [1] and confirmed by plasma characterization via optical emission spectroscopy [2,3], an easier plasma ignition is also anticipated. In this paper, we present preliminary results of an Alumina plasma chamber IS03 H^- source [4] operated without magnetic cusp. Operation under monthly cesiation induces a slow evolution of the molybdenum cesiated surface correlated with an increase of the co-extracted electron yield. An improved stability of the extracted H^- beam is achieved by compensating the Cs-losses.

The high intensity option for Linac4 features an adaptation of BNL's Magnetron. Simulation of this complex H_2-Cs arc discharge plasma, where electrons are emitted from a cesiated molybdenum cathode, requires characterization of the plasma impedance and knowledge of hydrogen and cesium densities. We present a measurement of plasma impedance over the range of discharge current, hydrogen and cesium-densities.

INTRODUCTION

The proton injector of CERN, a 50 MeV linear accelerator retires from operation by the end of 2018, it will be replaced by a 160 MeV H^- accelerator (Linac4) that is being commissioned. The initial specification featured a beam intensity of 80 mA and 0.4 ms duration within the acceptance of the RFQ. An increased pulse duration to 0.6 ms and an H^- beam intensity after the RFQ of 25 mA are suitable to cover today's CERN needs. However, the LHC Intensity Upgrade (LIU) requires Linac4 to deliver a beam intensity of 40 mA at 160 MeV during 0.6 ms. While the beam intensity is within reach of today's H^- sources, dedicated optimization is mandatory to minimize the beam emittance. Highest possible availability and reliability of the ion source is mandatory. Stability (2% intensity pulse to pulse), and flatness (5% for 0.6 ms pulse duration and 2% for short pulses) are not met yet and require further analysis and optimization. Systematic monitoring and addressing of all performance driving parameters is key to the success, the achievement of the SNS team is a perfect illustration of this method [5].

We present the experimental results of a cusp free plasma generator, which may improve the operational reliability and stability of the ion source. Magnetic cusps are standard features of ion sources with internal plasma heating (i.e. filament), their role is to reduce electron losses to the walls. Simulation of RF-ICP plasma heating has shown very clearly that the presence of magnetic field in the electron acceleration region reduces heating efficiency [1]. This result is confirmed experimentally via Optical Emission Spectroscopy by modelling and analysis of the plasma parameters obtained with and without magnetic cusp [2,3]. The original plasma electrode aperture diameter is 6.5 mm, a smaller diameter (5.5 mm) reduced the beam intensity. Therefore, this unit is equipped with a larger diameter plasma electrode aperture. The beam dynamics studies focus on optimization of the extraction geometry to minimize emittance growth. A first glimpse of the volume mode result is presented in [6]. A faraday cup placed downstream 4 plates with an aperture and a phase advance chosen in such a way that a particle passing all four aperture will fall in the acceptance of the RFQ is installed and being commissioned at Linac4's ion source test stand.

LINAC4 CUSP-FREE RF-ICP H$^-$ SOURCE

The IS03 cusp free unit is presented in figure 1, its main components are: alumina plasma chamber, 5 turn RF-coil, puller dump electrode and ground electrode. The plasma of Linac4 H$^-$ source is heated by up to 100 kW of 2 MHz Radio Frequency, which is Inductively Coupled to the hydrogen plasma (RF-ICP). The ISO3 ion source and its beam extraction optics are described in references [4,7]. The valve for pulsed hydrogen injection has been changed to a Parker electromagnetic valve (serial number 9-1421-900). The configuration of the beam extraction used for the cusp free tests was: plasma electrode aperture diameter: 7 mm, extraction gap: 3.35 mm (nominal 4.35 mm) and puller aperture diameter: 9.7 mm. The temperature controlled cesium oven is connected to the back of the plasma chamber (fig. 2).

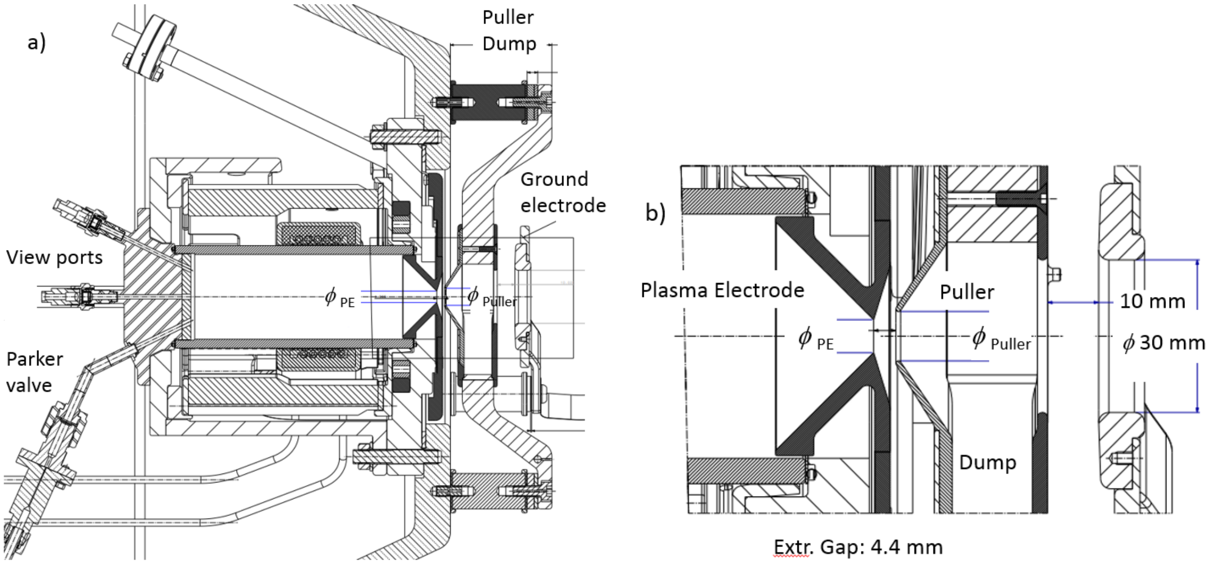

FIGURE 1. a) Layout of the ISO3 cusp free ion source, encompassing plasma chamber, 5 turns RF-coil, puller dump electrode and ground electrode. The electromagnetic valve for pulsed hydrogen injection (Parker valve) and the sapphire view ports are indicated. b) Detail of the beam formation and extraction regions, the plasma electrode (-45 kV), extraction gap, puller dump (-35 kV) and ground electrodes relevant for beam optical simulation are shown.

The IS03 H$^-$ source features an adjustable extraction gap based on washer thickness and straightforward exchange of plasma electrodes. After modification of the extraction optics, each electrode aperture is aligned on beam axis with its centring tool. The electron dump magnet pair is mounted on the puller-dump electrode, displacing the electrode induces a modification of the magnetic field in the extraction gap of ~1 mT/mm (mean field: 10-11 mT). Increasing the plasma electrode aperture modifies the electron path and may lead to slightly reduced dumping efficiency or generation of secondary electrons. The system is robust enough to swallow these minor changes during tests, once a new optimum is identified, it will trigger a beam optics optimization.

The cusp free H$^-$ source was conditioned in volume mode, after 7 days, the H$^-$ beam intensity reached 29 mA with an electron to ion ratio (*e/H*) of 41±3 and a RF-power yield of 0.8 mA/kW. The electron current contributes to space charge forces in the non-compensated beam extraction region. At low energy, an *e/H* value close to the H$^-$ to electron velocity ratio $(m_{H-}/m_e)^{1/2} = 42.87$ doubles the H$^-$ beam induced space charge. After cesiation the electron to ion ratio dropped below 1 and a 62 mA H$^-$ beam was extracted, the RF-power yield reached 2 mA/kW. The peak current corresponds to plasma chambers equipped with Halbach offset octupole cusps of about 1 mA/kW RF-power yields.

Shortly after cesiation, we reduced the distance between the plasma electrode and the puller from 4.4 to 3.4 mm. Two measurement periods (7 and 9 hours) dedicated to parameter scans of the H_2 injection, RF-power and RF-frequency during which the *e/H* were 3.5 and 4.5 provided 1800 sets of data. The coverage of the operation parameter space provides experimental background to modeling such as RF-coupling studies [8]. Automation of the source operation [9] demands an operation phase space with identified boundaries within which the system reacts to parameter changes in a predictable and preferably smooth and continuous manner. From the data set we can identify guide lines that will refine the controls algorithms: for examples: The RF-coupling is best matched for a RF phase equal to 0; the H^- yield is very responsive to hydrogen injection fluctuation (a 5% of EM-valve opening corresponds to a 30% variation of the H^- beam intensity); and excessive hydrogen injection will increase plasma light emission but reduce the H^- beam intensity.

IS03 cesiated surface sources operate under monthly injection of typically 5 mg of metallic cesium, during the cesiation process, the source is sealed off from the linac by closing a vacuum valve located in the Low Energy Beam Transport (LEBT) section. The IS03 source is re-cesiated once an *e/H* ratio of 8 is reached corresponding to a 20% increase of the space charge forces in the extraction region. The SNS source plasma is maintained at lower density by a secondary low power CW RF circuit to keep the plasma ignited between the 60 Hz high power RF pulses; which keeps Cs ionized and possibly reduces the loss rate through the plasma electrode aperture. At CERN's low repetition rate, the hydrogen is pulsed and the plasma extinguishes between pulses. Metallic Cesium's high vapour pressure is likely to contribute to Cs-losses from the plasma chamber through the plasma electrode aperture. Larger amounts of Cesium could be injected monthly; disposing of a Cs inventory suitable to compensate losses keeps a low *e/H* as observed on an IS02 prototype, however, we aim to develop an operation mode that minimizes Cs-consumption. The Cs-Loss Compensation (CsLC) mode consists, after a few mg cesiation, in leaking into the plasma chamber a minimal Cs-flow to stabilize the cesiated inner surface of the molybdenum plasma electrode. This mode is necessary when operating with deuterium that is impaired by a fast degradation of the cesiated surface [10]. The CsLC process is monitored via the electron to ion ratio and H^- yield.

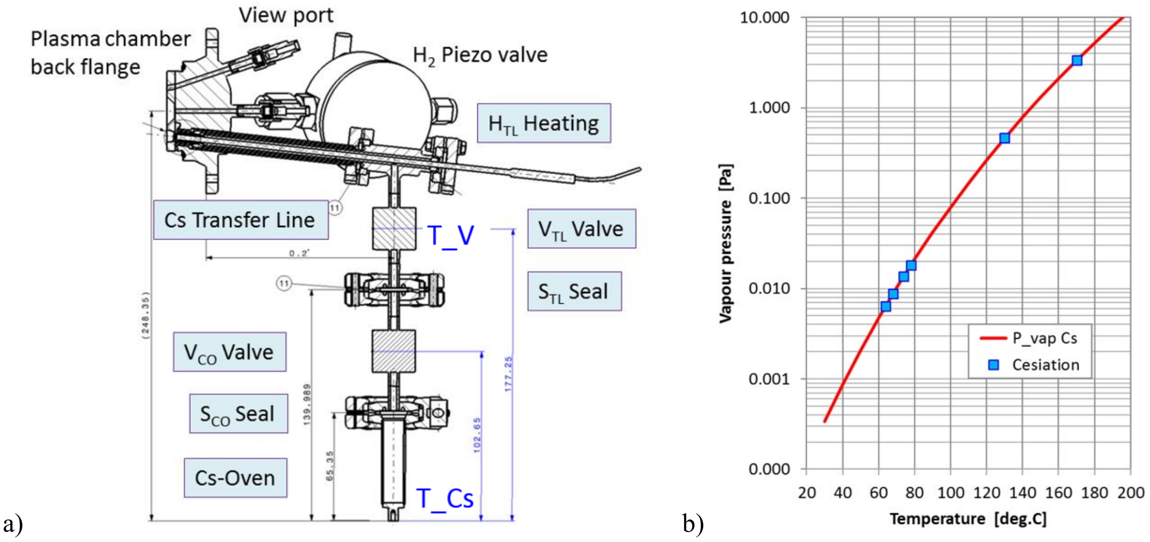

FIGURE 2. a) Layout of the Cs-delivery system, the Cs-oven, valves and transfer line are heated by independent circuits, Cs-Oven and valve are temperature controlled. b) Cs-vapor pressure characteristic, the Cs-Oven operating points of cesiation or Cs-loss compensation tests are indicated.

Cs-loss compensation was tested on the cusp free IS03 unit. The first week was without CsLC and the second week, after a short re-cesiation, the source was operated in CsCL mode, tuned once a day to its maximum H^- yield (H^- beam current : 67 mA) and during few hours to 47 and 35 mA. The first week, the co-extracted electrons increase correlated to the H^- beam decrease. The second week the *e/H* stayed below 1 and the H^- current was stable (all pulses within 5%). The transfer line presented in figure 2 a) was kept at nominal temperature while the temperature of the valve and Cs-oven (respectively) were daily reduced from (90˚C, 78˚C) to (75˚C, 63˚C). The short test result is promising; we never reached this level of stability at highest beam intensity before. Of course, extrapolating to one-year operation requires multi month validation. According to previous Cs-oven calibration and the vapour pressure of metallic cesium presented in figure 2 b), the expected Cs consumption shall range from 82 to 235 mg/year (63˚C to 78˚C).

Hydrogen Dynamics

Piezo and electromagnetic valves are operated as pulsed hydrogen injectors, the gas density is a key factor during plasma ignition and beam extraction. We operated Piezo valves at CERN and noticed their temperature dependence, Magnetron H^- sources are successfully operated with electromagnetic valves; we tested two models from Parker with 0.5 and 1.0 mm injector aperture diameter. The hydrogen injection test stand is equipped with a fast hot cathode ionization gauge (Baltzers IMR-312) located in a mockup of the IS03 plasma chamber and a dual gauge (Pfeiffer PKR) located above the pumping unit. The IMR gauge signal is split before entering its readout box and measured on a digital oscilloscope, the delay induced by the cabling and the 1 MΩ input resistor (RC=200 µs) compares to the expected gas dynamics, it was reduced to 20 µs by adapting the readout resistor to 100 kΩ. In order to reduce noise, we average over 20 gas pulses. Figure 3a presents typical pressure measurement of the Parker 1 mm aperture valve. The PKR gauge signal is delayed by the conductance of the 6.5 mm plasma electrode aperture. Figure 3b presents 3 pairs of curves selected to deliver similar amounts of hydrogen, the feed pressure and the EM-valve opening time (expressed in µs) are indicated. The 1 mm aperture EM-valves requires a longer opening time but the shapes are similar and when tested on IS03 units they operated successfully.

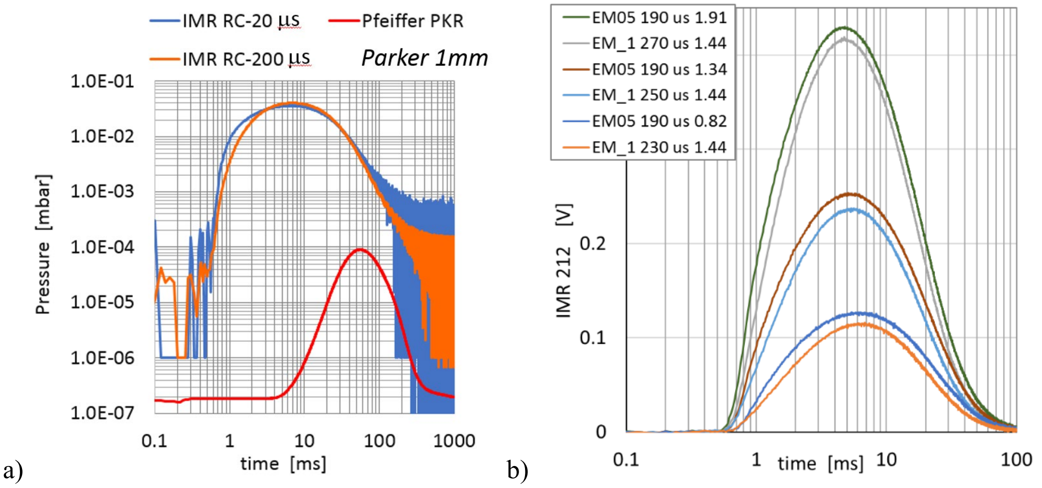

FIGURE 3. Illustration of the measurement at the pulse hydrogen injection test stand: a) pressure measurement from the IMR fast gauge in the plasma chamber mockup and PKR gauge in the pumping unit. The average (20) IMR gauge signal is measured on a digital oscilloscope, the time constant of the 100 kΩ readout is 20 µs. The PKR gauge signal is delayed by the conductance of the 6.5 mm plasma electrode aperture. b) The dynamics of two parker valves with aperture diameter of 0.5 mm (noted EM05) and 1 mm (EM_1) are compared for similar H_2-pulses, the valve opening time and the feed pressure (unit: bara) are indicated.

The IS03 sources operated with the 0.5 mm aperture EM-valve did not respond linearly in particular close to the optimum operation domain. The hydrogen feed pressure had to be increased and despite this, beam intensity fluctuations were noticed. The response of the EM valves to opening time is presented in figure 4a, the amount of gas and the pressure during plasma ignition and beam delivery are given. The non-linearity of the 0.5 mm unit is very clear; the 1 mm unit provides a broader continuous operation rage that shall ease operation. The feed pressure dependence of the 0.5 mm unit (fig 4b) is quasi linear. Within the tuning capabilities offered by the feed pressure and the opening time, electromagnetic and piezo valve [11] cover the source requirements. This setup will be used to investigate the pulse-to-pulse stability, the response to temperature changes and the long-term stability of these valves.

CERN's copy of BNL's magnetron is equipped with a 0.5 mm EM-valve. From the injection dynamics and the amount of gas injected, the order of magnitude of the flow passing through the magnetron could be estimated.

However, the anode heating needed to operate the magnetron at 0.8 Hz may have an impact so a heating/cooling system to control the temperature may be required.

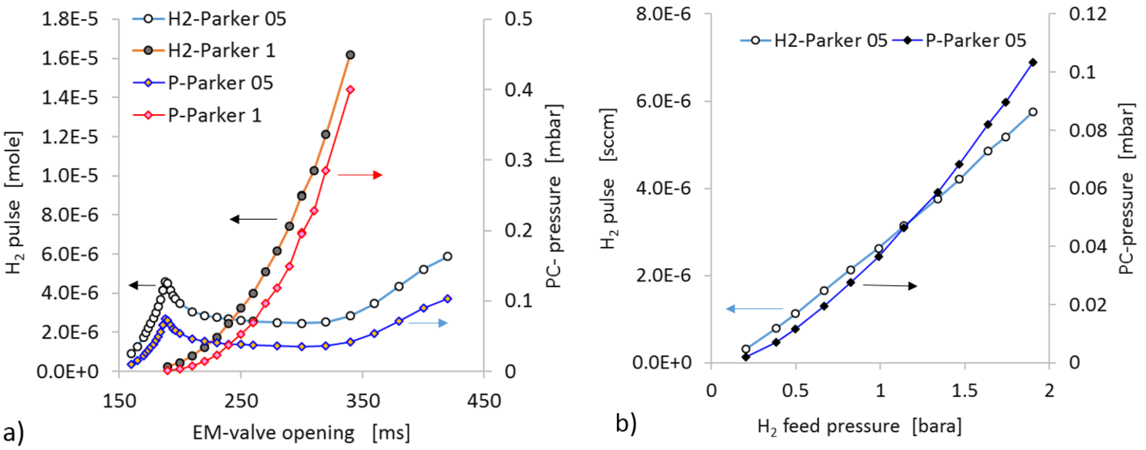

FIGURE 4. a) Calibration of the Parker electromagnetic valves Serial type 9, the plasma chamber (PC) pressure is averaged in the time range typical for plasma ignition and beam extraction: 1 to 2 ms following EM-valve opening trigger. b) Parker EM-valve 0.5 mm: H_2 feed pressure dependence of the gas pulse and pressure, valve opening time 190 μs.

MAGNETRON DISCHARGE

BNL's magnetron H^- source has demonstrated beam intensities well beyond Linac4's requirements; measurement of its beam intensity within Linac4 RFQ's acceptance is pending. Optimizing the beam formation and extraction region will be a challenging task; but very likely worth the effort.

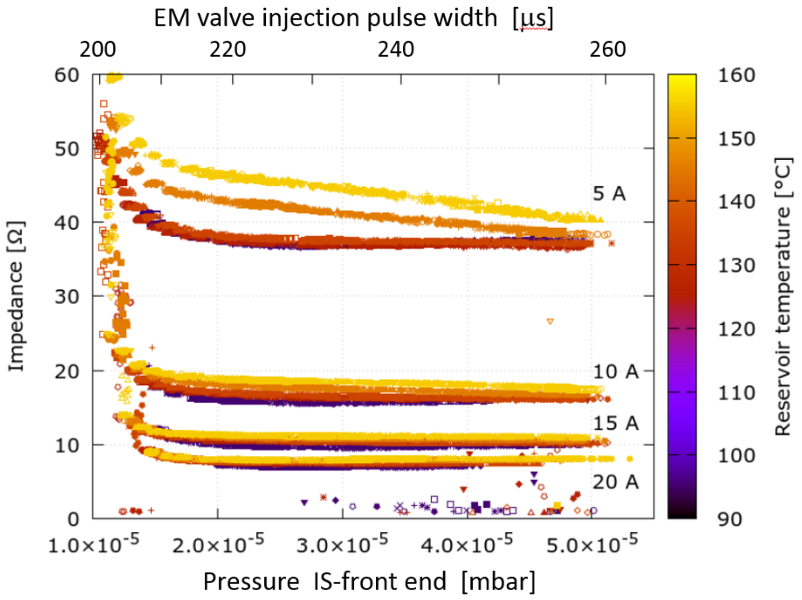

FIGURE 5. Impedance mapping of CERN's copy of BNL's heated anode magnetron operated at 0.8 Hz. The temperature of the Cs-Oven is color-coded Cs Temp: 155 ˚C, yellow and 110˚C dark blue. The current of the discharge, the pressure in the front end and the duration of EM-valve opening is indicated.

The very compact design limits diagnostics capabilities to a few temperatures, spectroscopy of the complex expanding Cs-H plasma in the beam formation region and plasma impedance. Starting with the simplest, we performed a parametric scan of the hydrogen, cesium and discharge current operation space (fig.5). The calibration of the Cs-Oven allows to derive the mass flow and EM-valve calibration on a dedicated mock-up shall provide the shape and intensity of the hydrogen flow during the discharge. During these tests, the Cs-Oven temperature was higher than in BNL's operation, future tests would have to be performed at lower temperature.

SUMMARY AND OUTLOOK

The IS03 ion source operated with a cusp-free alumina plasma chamber delivered the performances expected from plasma simulation validated by optical emission spectroscopy analysis and is the new "standard" Linac4 H^- source. Operation under strong suppression of co-extracted electrons is very stable even when operated at the peak performance of the ion source and the plasma ignites smoother without initial electron burst. This limited duration test is promising but not sufficient to determine the minimal flow required to suppress co-extracted electrons (e/H<1) nor to demonstrate that this level of performance can be maintained at one-year time scale. The operation with plasma electrode aperture of 7 mm was positive; lager diameter and tilted extraction compensating the filter and dump field induced beam misalignment are available for tests. The IS03 dump is designed to accept volume mode co-extracted electron currents of up to 3 A, the emittance improvement potential of optics specific to very low co-extracted electron yields is worth investigating conditioning and operation extraction optics would be different.

Parametric analysis of the operation phase space is the solid complement required to machine learning based operation survey or source controls software and shall be implemented at regular intervals. Calibration of the non-directly accessible parameters such as cesium flow rates and hydrogen pressure will be improved to provide consolidated data to simulation teams. We will evaluate further Piezo and EM-valves types. RF-pulse and gas injection are the driving parameters of the Linac4 source pulse-to-pulse stability and beam flatness, we noticed their correlation.

Optimization of the beam formation and extraction region are on-going and will be experimentally validated at the ion source test stand now equipped with an emittance meter and an RFQ-acceptance mask [12] providing a direct measurement of the expected transmission through the RFQ.

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