RF Trap for Chip-scale Helium Ion Pump (RFT-CHIP)

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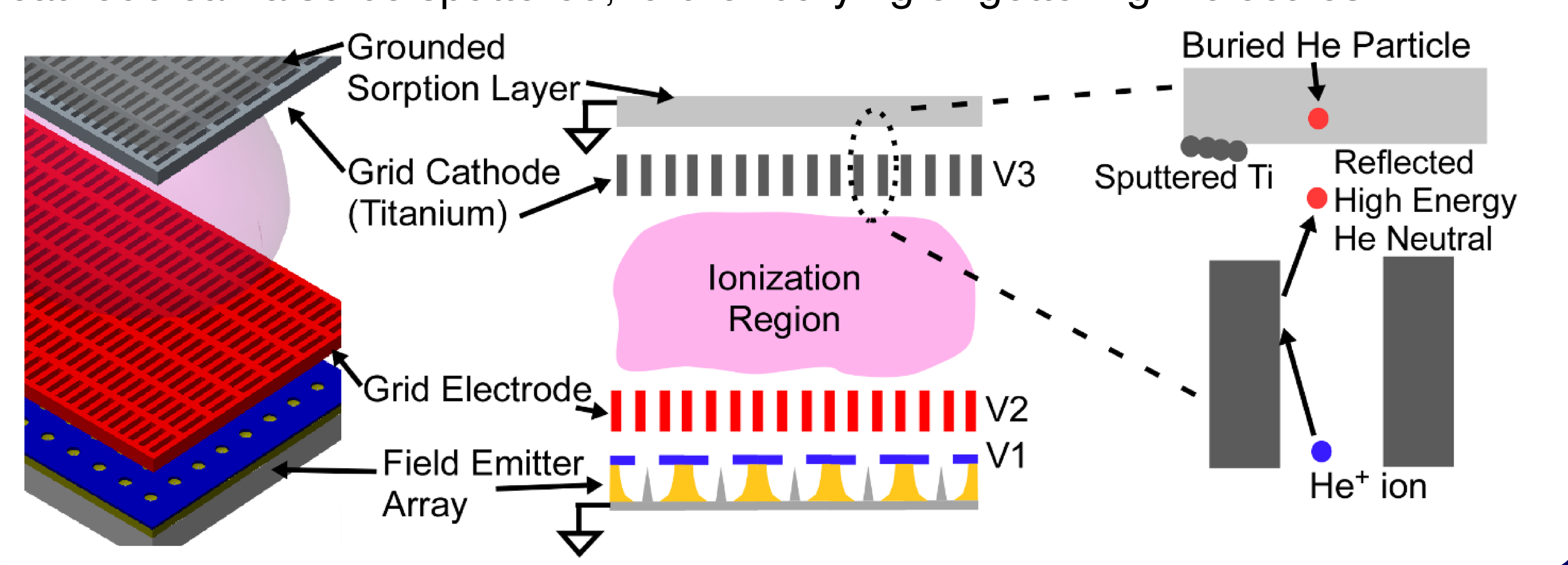
Summary: We report the first miniaturized magnet-less RF electron trap for use in chip-scale atomic instruments. Chip scale atomic inertial measurement units (AIMUs) and chip scale atomic clocks (CSACs) require ultra high vacuum operating conditions. Passive pressure control (low leakage packaging and getters) does not provide a long term solution for Helium intrusion. The atomic devices are sensitive to magnetic fields; thus low power active pumps that *do not require magnets* are desirable. Typical ultra-high vacuum pumps use crossed magnetic fields to trap electrons and ionize gas. Instead, we investigate a chip-scale ion pump (~1 cm³) that will utilize RF electron trapping, stacked micromachined elements, and a triode configuration to maintain the ultra-high vacuum (1 nanoTorr). This will provide a magnet-less ionization and pumping solution at ultra-high vacuum with relatively low voltage (<500 V), potentially enabling atomic microsystems and miniaturized mass spectrometers.

1 CHALLENGE AND INNOVATION

Challenges: 1) Helium is non-reactive and difficult to efficiently getter; 2) AIMUs are sensitive to magnetic fields, while macro-scale ion pumps require magnets; 3) Ultra-high vacuum requirements present special challenges for chip-scale pumps, especially minimizing parasitic particle-wall collisions.
Innovations: 1) Ionization with field-emitted electrons with subsequent trajectories lengthened via RF voltage; 2) Slotted cathode for generating and burying high energy neutrals for enhanced noble gas pumping; 3) Sputterable titanium cathode for pumping of reactive gases that may be desorbed during pump startup or due to thermal transients; 4) "Triode" configuration for protecting pump elements during ion sorption and avoiding release of buried gas particles.

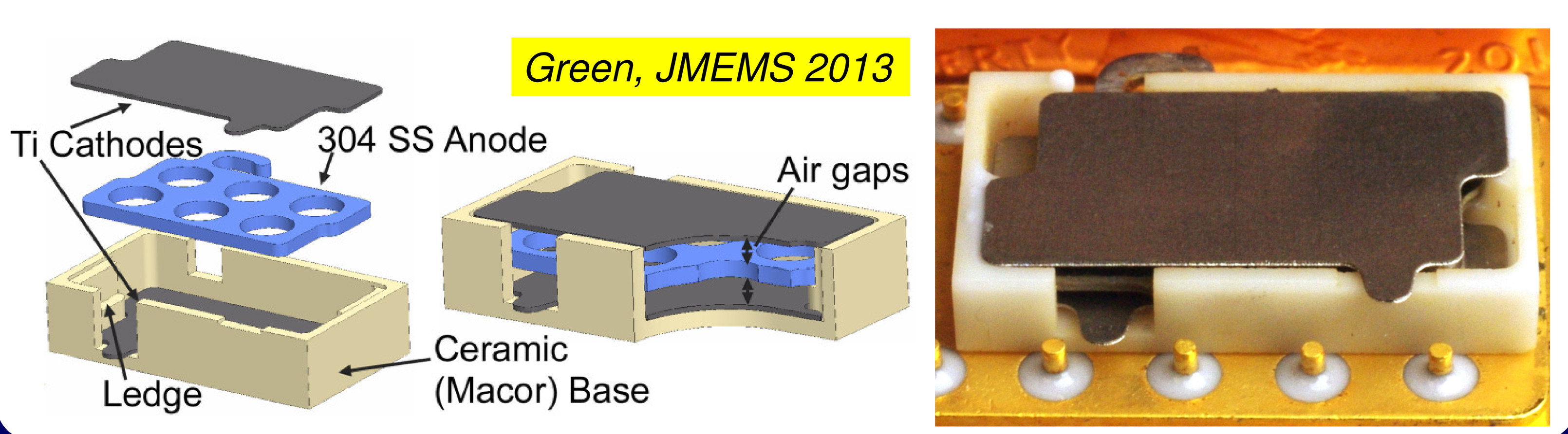
2 APPROACH

Electrons generated by field emitter → Electrons trapped in ionization region by RF voltage → Electrons ionize gas molecules → Ions accelerated into the grid cathode → Ions neutralized and deflected, buried in the sorption layer. Ti cathode can also be sputtered, further burying or gettering molecules.



3 PREVIOUS WORK

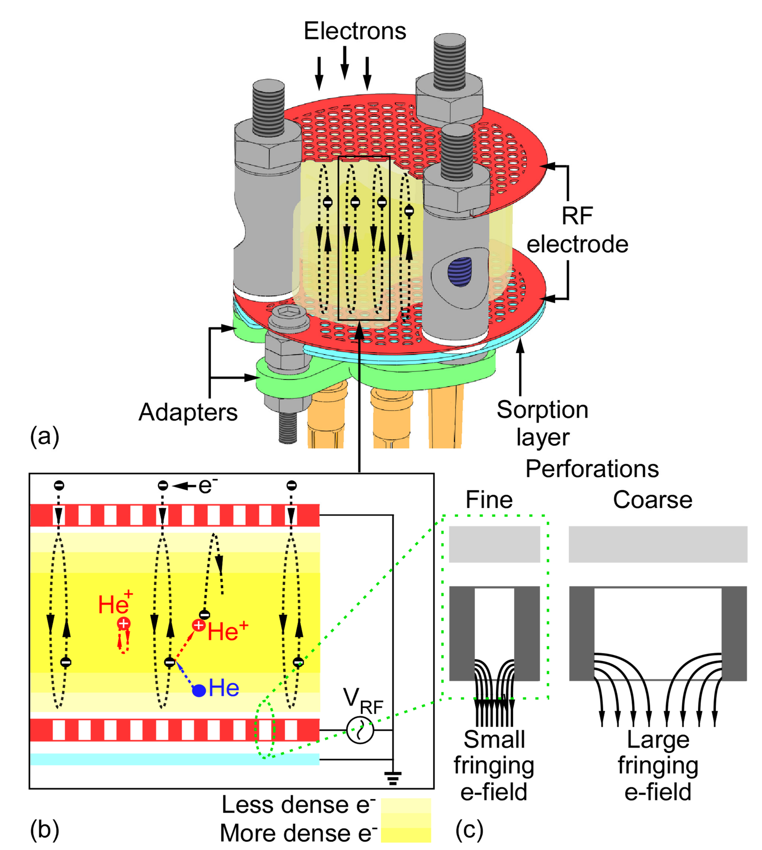
Previous work under the DARPA HiVac program pursued a miniaturized, chip-scale Penning cell array for sputter-ion pumping. The device was ≈0.2 cm³ in volume, without including magnets or the magnetic circuit. Experiments showed that the architecture is capable of operating at a pressure at least as low as 1.5 µTorr with magnets in place. While located in a 2.5 cm³ package, the pump reduced pressure to <10 mTorr from a starting pressure of 115 mTorr in ≈4 hours of operation with 450-600 V applied across the device, consuming 100-250 mW.

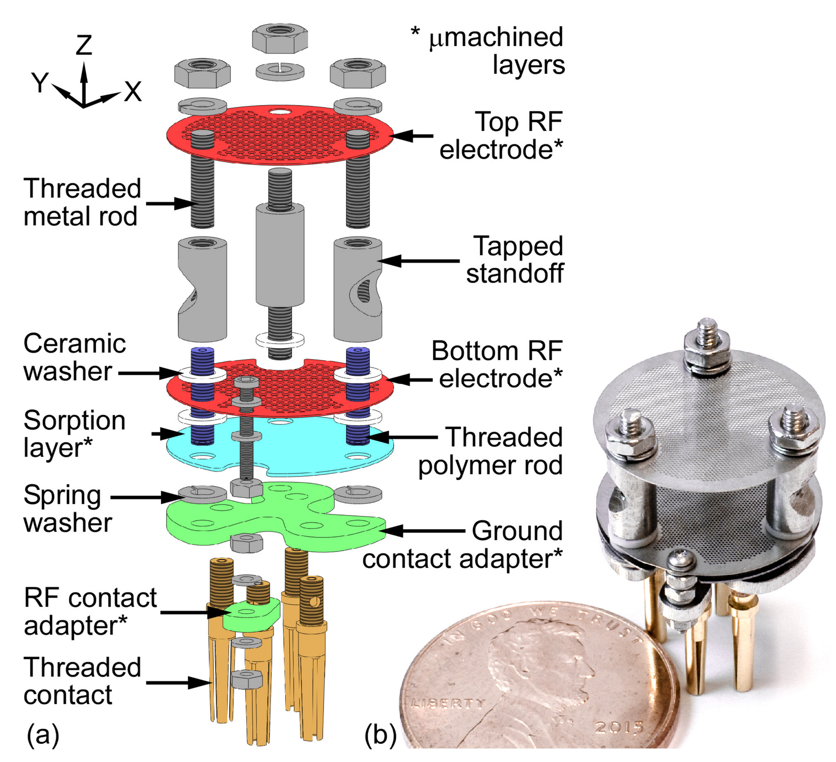


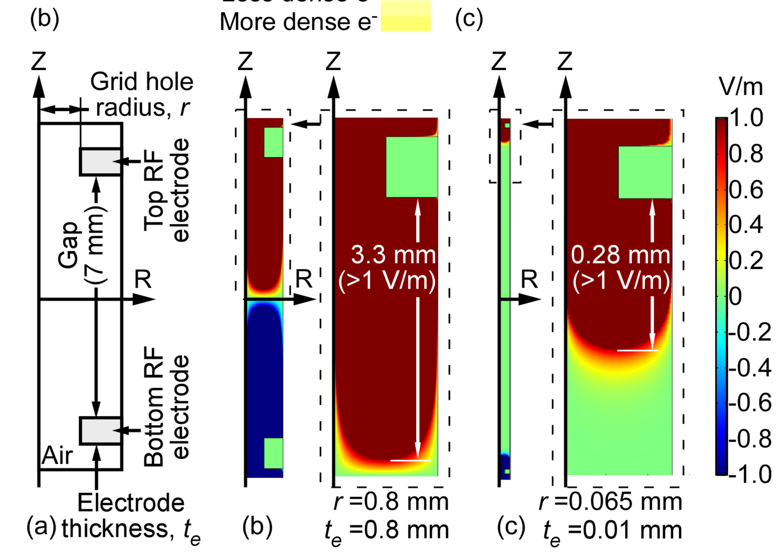
4 DESIGN AND MODELING

Enhanced-efficiency Electron Trapping Module (E³TM)

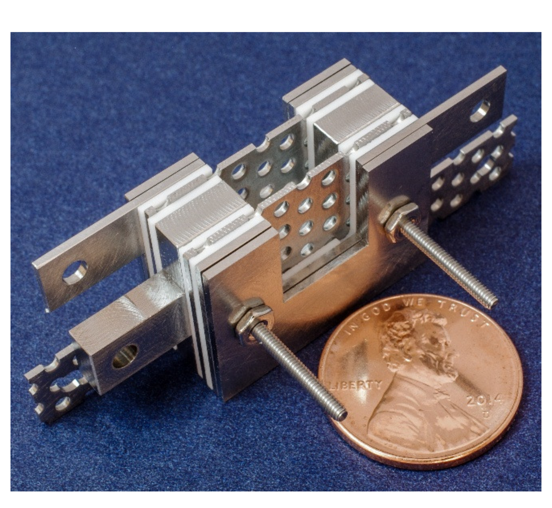
- Excellent volume utilization (75.7%)
- Finely perforated titanium grid electrodes to enable uniform electric fields to trap electron for a longer time (photochemical machining)
- Few metal electrodes and less exposed dielectric to reduce parasitics and simplify RF characterization
- Built on a 9-pin, subminiature-C 1.33" CF feedthrough to realize electrical connections and mechanical supports
- Tantalum sorption layer to potentially enhance the noble gas pumping (µEDM)



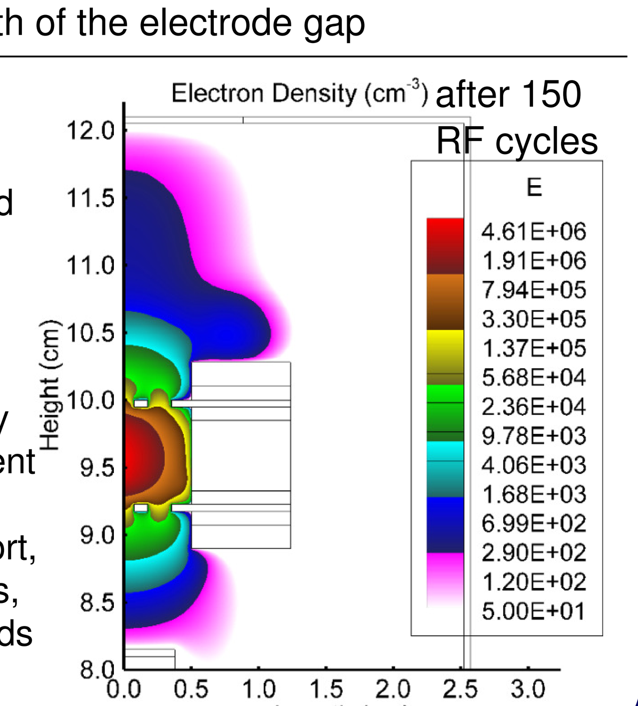




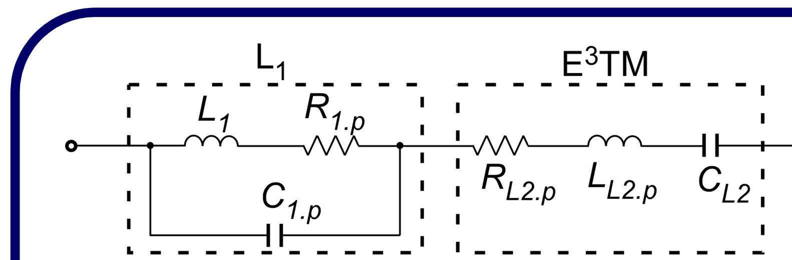
- Micromachined perforations in RF electrodes reduce lateral fringing fields compared to larger perforations
- Reduced lateral fields allow the electrons to oscillate between the electrodes with reduced lateral drift
- Electrons can get closer to the electrodes without experiencing large lateral drift; thus extends useful trapping volume to nearly the full length of the electrode gap

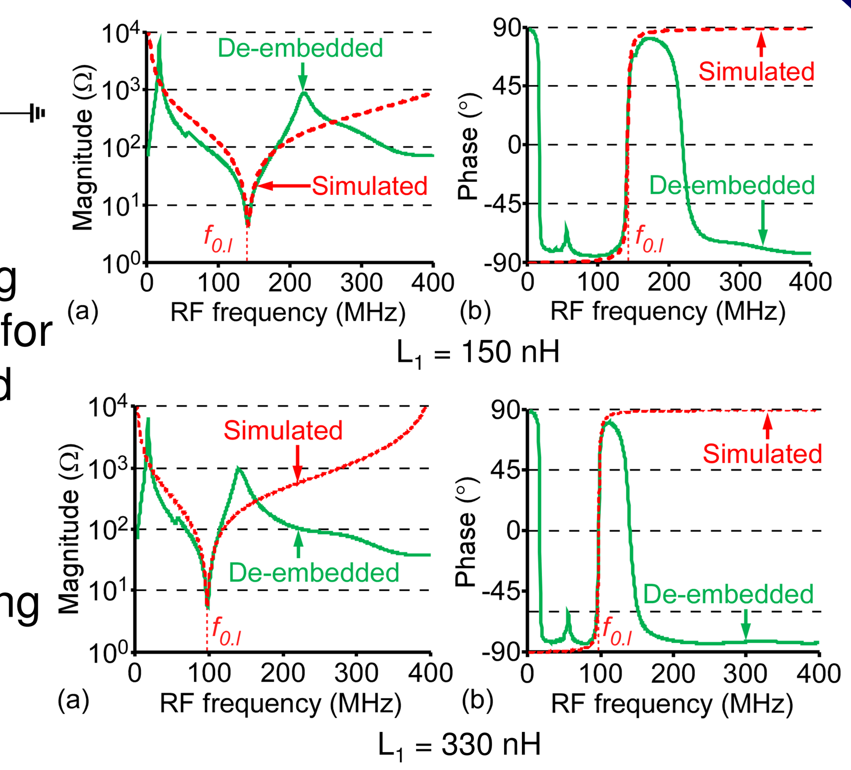


- 1st generation used conventionally machined layers
- Complicated RF impedance
- Low active volume to device volume efficiency
- Hybrid Plasma Equipment Modeling (HPEM) uses charged particle transport, ionization cross sections, and Monte Carlo methods to estimate ~1000x densification within trap

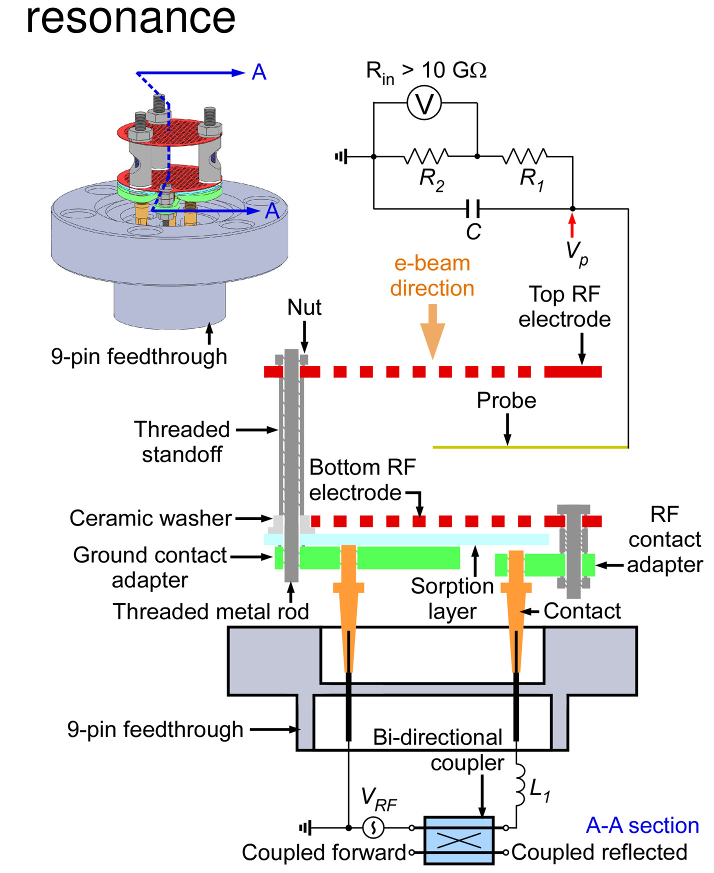


5 RESULTS

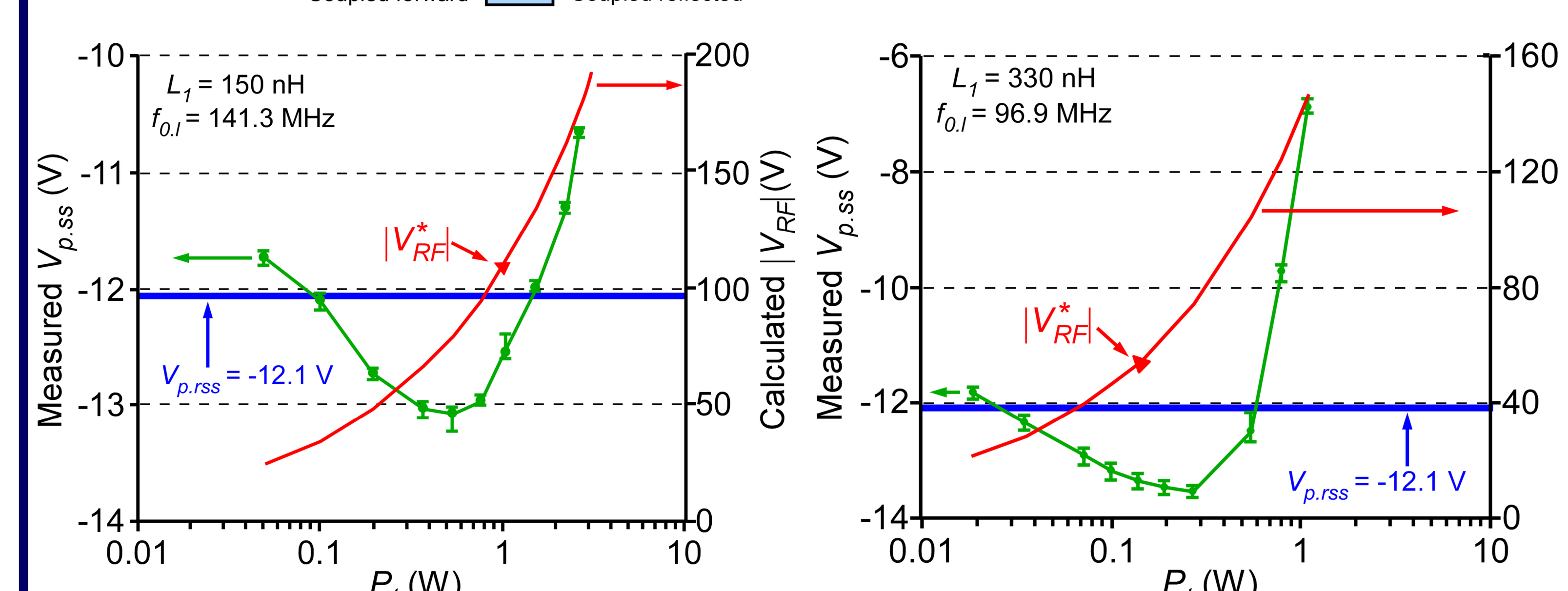




- (Above) Circuit model representing device and series inductor, useful for predicting frequency response and estimated trapping voltage versus input power
- (Right) Simulated and measured impedances match well at operating resonance



- External electron beam injects electrons into trapping region
- DC measurement scheme, including a capacitor and resistor network, correlates DC potential at probe (V_p) to electron density in the trapping region
- External inductor L_1 sets device operating/resonant frequency
- Bi-directional coupler measures forward and reflected RF power during operation



- More negative steady state probe potentials (SSPPs, $V_{p,ss}$) than reference SSPPs ($V_{p,rss}$) indicates electron densification in the electron trapping region due to RF signal
- Limited band of RF power levels (voltages) leading to electron densification agrees with analytical and numerical modeling
- Good agreement between analytically expected optimal RF voltage (V^*_{RF}) and experimentally measured most negative SSPP (highest densification)
- Analytical estimates of electron density are ~2 x 10⁶ cm⁻³, which is 10⁴ times larger than the electron density within the e-beam.

Markosyan et al. "Miniaturized magnet-less RF electron trap. I. Modeling and analysis," *J. Vac. Sci. Tech. B*, **35**(4), 2017
Deng et al. "Miniaturized magnet-less RF electron trap. II. Experimental verification," *J. Vac. Sci. Tech. B*, **35**(4), 2017
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