

Investigation of sputtering and erosion phenomena in radio-frequency quadrupoles

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The performance and stability of radio-frequency quadrupoles (RFQs) depend critically on the structural integrity of their electrodes (vanes or rods), which are subjected to high-intensity ion beam exposure during accelerator operation. This study investigates the sputtering induced vane erosion on the European Spallation Source (ESS) RFQ, a critical component of the ESS linear accelerator. Particle tracking simulations for the determination of RFQ beam loss profiles were coupled to SDTrimSP software (static-dynamic transport of ions in matter sequential-parallel processing) modeling to estimate the sputtering yield distribution and the resulting erosion rates under nominal operating conditions. Methodology validation and benchmarking was performed using quartz crystal microbalance (QCM) measurements employing proton (2, 6 keV) and argon (Ar^+ 2 keV, Ar^{6+} 36 keV) ion beams with incident angles of 0° – 70° . The QCM experiments were used to benchmark SDTrimSP software simulation parameters for the calculation of sputtering yields and total electrode erosion rates across the energy and angular ranges relevant to the ESS RFQ. The results and conclusions are extended to RFQs employed for heavy-ion acceleration providing insights into long-term stability and performance degradation. The results indicate that heavy-ion irradiation leads to significantly higher sputtering yields and erosion rates compared to protons. It is estimated that the increased erosion rates result in critical frequency perturbations in RFQ cavities especially in high current or cw configurations that need to be effectively compensated.

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I. INTRODUCTION

The European Spallation Source (ESS) is a research facility currently under installation and commissioning at Lund, Sweden, consisting of a particle linear accelerator (linac), a solid rotating tungsten (W) target and up to 24 experimental instruments for neutron-based research. The linac will produce a 2.86 ms pulsed proton beam with peak current of 62.5 mA and repetition rate of 14 Hz, reaching the nominal energy of 2 GeV at the entrance of the target [1]. A radio-frequency quadrupole (RFQ) is a vital component of the ESS normal-conducting linac as it provides the initial focusing, bunching, and acceleration of the proton beam [2]. The ESS RFQ was delivered by CEA-Saclay equipped with four (4) modulated vanes as electrodes and a total length of 4.55 m separated into five (5) sections [1]. Oxygen-free

electrolytic Cu-OFE/CW009 (99.99% purity) was selected as the main RFQ material for its excellent thermal and electrical properties used for the cavity body, vanes, and cavity ports. The manufacturing process includes three-stage 3D hot forging and multiple annealing cycles under vacuum in order to eradicate material stress in addition to a high isostatic pressure treatment to eliminate millimetric shrinkage defects and control copper porosity [1].

ESS availability and reliability requirements [1] require careful consideration of how cavity materials perform under beam exposure. The comprehension of beam-material interactions and their effects is therefore essential in order to ensure consistent performance during operation [3]. Ion beam exposure triggers a range of complex interactions and mechanisms, leading to the formation of structural defects that significantly influence material performance across multiple scales [4]. The accelerator technology community has shown increasing interest in understanding how cavity losses and radiation-induced damage affect material properties, particularly in the context of high-power, high-intensity RFQ designs [5,6]. In a recent study, Serafim *et al.* examined the effects of H^- induced hydrogen blistering on the dielectric strength of

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RFQ copper surfaces [7,8]. In addition, beam losses introduce microstructural damage in RFQ copper, leading to reduced thermal conductivity [9]. In the context of RFQ cavities, it is well established that local variations in vane geometry on the order of tens of micrometres can introduce perturbations in the resonant frequency and electromagnetic field distribution, affecting cavity performance [10–12]. Moreover, modifications in surface roughness could lead to increased electrical breakdowns and interlocks, impairing the ability to sustain the RFQ cavity field [13]. Within this framework, sputtering emerges as a significant process influencing both surface roughness and RFQ vane erosion. Surface atoms are removed from the solid due to recoil cascades that return to the surface and provide nearby atoms sufficient energy to escape the target material followed by the emission of secondary electrons [4,14,15]. The erosion of the surface is characterized by the sputtering yield ($\mathcal{Y}$), defined as the amount of sputtered atoms per incident ion. The sputtering yield is strongly influenced by factors such as the target's elemental composition, surface morphology, and the characteristics of the incoming ion beam, including its energy and angle of incidence [14–17]. The objective of this study is to investigate the effects of beam-induced sputtering on the RFQ electrode surfaces (vanes) during nominal operation of the ESS accelerator and to extend this analysis to RFQ cavities designed for heavy-ion acceleration. Particle tracking simulations were performed to determine the energy and angular distributions of the proton beam losses in combination with binary collision approximation (BCA) SDTrimSP [18] simulations for sputtering yield ($\mathcal{Y}$) evaluation. Simulation results were benchmarked against experimental sputtering yield measurements conducted at the Institute of

Applied Physics at TU Wien, employing the quartz crystal microbalance (QCM) method. Sputtering yield measurements were conducted at multiple incidence angles (0° – 70°) using Ar^+ (2 keV), Ar^{6+} (36 keV), and proton beams at 2 and 6 keV. Experimental results were used to validate SDTrimSP parameters, allowing for sputtering yield simulations at higher energies (40–130 keV) and impact angles (70° – 89°) relevant to RFQ beam losses in order to estimate annual vane erosion rates for proton and argon beams.

II. SIMULATION METHODOLOGY

A. RFQ proton beam loss analysis

ESS RFQ beam loss analysis was performed using the beam dynamics simulation codes Toutatis [19] and TraceWin [20] using an optimized Gaussian beam with an emittance of $0.25 \pi \text{ mm mrad}$ and following the methodology presented in [9]. The loss distribution and discretized vane geometry files obtained from the Toutatis/TraceWin simulations were used as an input to a purpose-developed Python script for the calculation of the incidence angle Θ with respect to the vane surface normal vector and vane angle α with respect to vane pole tip.

Initially, a momentum vector $\vec{p}_i = [p_{xi}, p_{yi}, p_{zi}] = [p_{zi}x_{pi}, p_{zi}y_{pi}, \sqrt{2M_p E_i/(x_{pi}^2 + y_{pi}^2 + 1)}]$ for each particle denoted with the index i can be obtained using the spatial coordinates $L_i(x_i, y_i, z_i)$, particle rest mass M_p , energy (E_i), and divergences (x_{pi}, y_{pi}) contained in the loss distribution file. These quantities can be calculated under the assumption of a nonrelativistic regime applicable to RFQ cavities as $\beta \ll 1$ in the initial stages of acceleration [21].

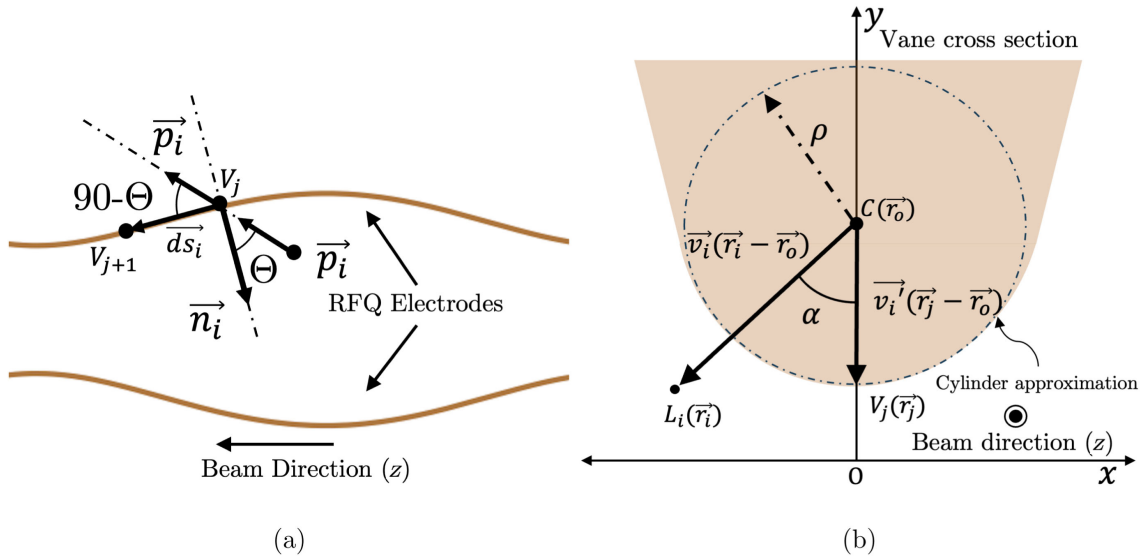


FIG. 1. (a) Illustration of the geometric method used to determine the particle incidence angle Θ relative to the local surface normal vector $\vec{n}_i$. Vector $\vec{p}_i$ corresponds to lost particle momentum vector and points V_j, V_{j+1} to discrete sequential vane geometry points. (b) Schematic representation of vane angle α calculation methodology with respect to vane pole tip via the definition of $\vec{v}_i, \vec{v}'_i$ vectors. The point L_i contains the spatial coordinates of the lost particle labeled by index i .

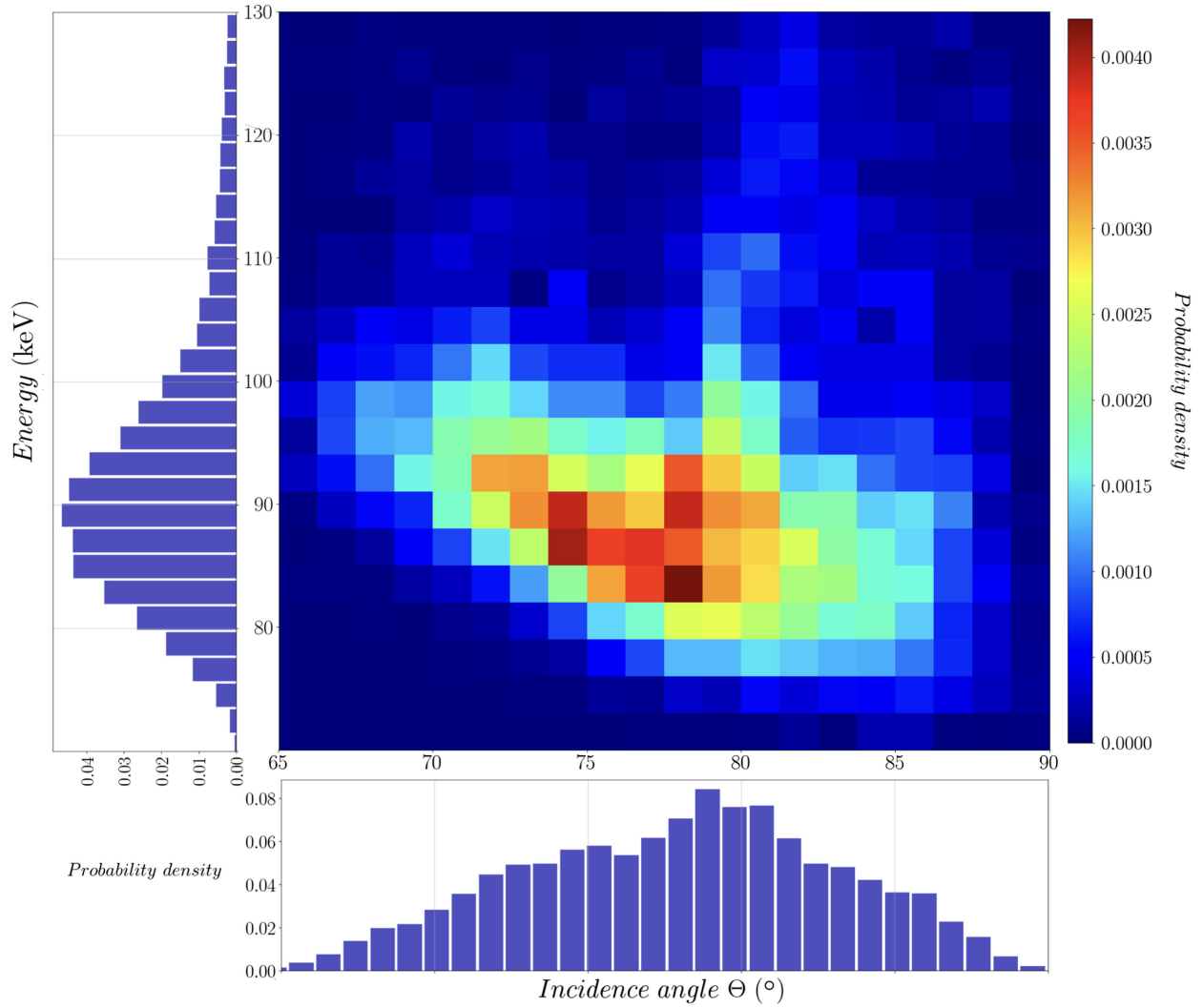


FIG. 2. 2D probability density function histogram plot for the ESS RFQ lost particles with respect to energy and incidence angle Θ . 1D histogram plots describe the distribution of the losses with respect to energy and incidence angle Θ .

At this point it has to be noted that the exact coordinates of the lost particles depend on the mesh and integration step used in the particle tracking simulations. Following the evaluation of the momentum vector, the algorithm detects the closest point $V_j(x_j, y_j, z_j)$ of the discretized vane geometry file to the point L_i where the particle was lost. Figures 1(a) and 1(b) show the definitions of the vectors and angles Θ , α used to evaluate the lost particle angular distributions throughout this study.

The incident angle Θ for each particle is obtained through the dot product of the vane surface normal vector $\vec{n}_i$ and momentum vector $\vec{p}_i$:

$$\Theta_i = \arccos\left(\frac{\vec{n}_i \cdot \vec{p}_i}{|\vec{n}_i||\vec{p}_i|}\right). \quad (1)$$

Subsequently, the incidence angle Θ can be obtained from its complementary angle, using the momentum vector $\vec{p}_i$ and the tangent vector $d\vec{s}_i$ with magnitude defined from

the adjacent vane points V_j, V_{j+1} . The angular distribution of losses on the vane tip profile (angle α) was determined via the formation of vectors $\vec{v}_i$ and $\vec{v}'_i$ [Fig. 1(b)]. The 3D geometry of the vanes is approximated by the construction of a cylinder with radius equal to the pole tip radius ρ (3 mm for ESS RFQ) and length of dz equal to the distance of the adjacent vane points V_j, V_{j+1} rotated to align with the direction of the tangent vector, $d\vec{s}_i$. Vectors $\vec{v}_i$ and $\vec{v}'_i$ connect the center of the tilted cylinder (C) with the vane surface point V_j and particle coordinate point L_i , respectively. Therefore, vane angle α with respect to the RFQ vane tip is calculated simply by the dot product of these vectors:

$$\alpha_i = \arccos\left(\frac{\vec{v}_i \cdot \vec{v}'_i}{|\vec{v}_i||\vec{v}'_i|}\right). \quad (2)$$

The above-mentioned analysis was performed for each one of the four RFQ vanes, and Fig. 2 presents the resulting

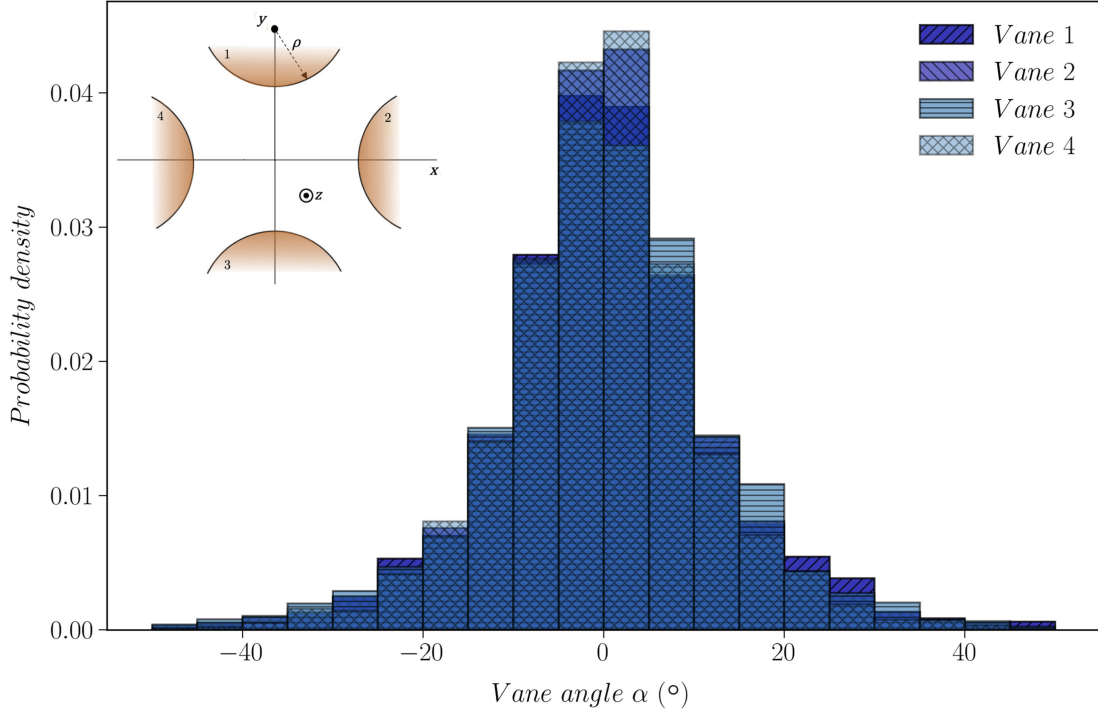


FIG. 3. Probability density function histograms of vane angle α of the RFQ lost particles with respect to vane tips. The results indicate a higher density of lost particles close to the vane tips and in the range $[-25^\circ, 25^\circ]$. The embedded plot presents the adopted RFQ vane naming convention.

2D density histogram of the ESS RFQ lost particles with respect to their energy and incidence angle Θ . The surrounding histograms present the energy and incidence angle Θ distributions. Based on the methodology outlined above, the calculated incidence angles fall within the range of 64° to 89° with respect to vane normal vector and the corresponding incident particle energies range from 75 to 120 keV. 1D and 2D histograms presented in Fig. 2 and throughout this manuscript represent the normalized probability density functions or the respective variables. Following the results provided in [9] losses are mainly concentrated on the first part of the RFQ (first 2 m), where the cavity behaves as a *shaper* and *gentle buncher*; thus the corresponding loss energy and angular range will be used in this study.

Moreover, it should be noted that this analysis corresponds to an optimized proton beam with a maximum transmission of 98.47% leading to total losses of 1.53% and does not account for high-loss scenarios that are commonly encountered during commissioning and operations. Toward the high-energy end of the RFQ, acceleration plays an increasingly important role, leading to the reduction of beam losses. Additionally, the values of calculated incidence angles are increased with particle energy, as higher final energies correspond to a larger longitudinal momentum component p_z of the lost particles.

The resulting histograms following the evaluation of vane angle α , representing the probability density function

$f(\alpha)$ of particle losses along the vane tip profiles, are shown in Fig. 3. The analysis indicates that losses are predominantly concentrated within the α angle range of $[-25^\circ, 25^\circ]$ relative to the RFQ vane tips highlighting the uneven erosion across different segments of the vane.

III. SPUTTERING YIELD MEASUREMENTS

A. Experimental methodology

Sputtering yield ($\mathcal{Y}$) measurements were performed at the Institute of Applied Physics, TU Wien, using the quartz crystal microbalance (QCM) method [22], which enables high-precision detection of mass changes by tracking shifts in the resonance frequency of a quartz crystal [23,24]. The sensitivity and reliability of the QCM method have established it as a widely adopted technique across both industrial and research environments with applications including coating process monitoring, thin film growth studies, and quantification of ion-induced erosion in materials [25–27]. The equation governing the rate of mass change is obtained from the time derivative of the resonance frequency in the fundamental relation of the QCM technique, as originally formulated by Sauerbrey [23]:

$$\frac{\Delta m}{\Delta t} = -\frac{m_0}{f_0} \frac{\Delta f}{\Delta t}, \quad (3)$$

where f_0 and m_0 represent the initial resonance frequency and mass of the quartz crystal. Since the rate of frequency

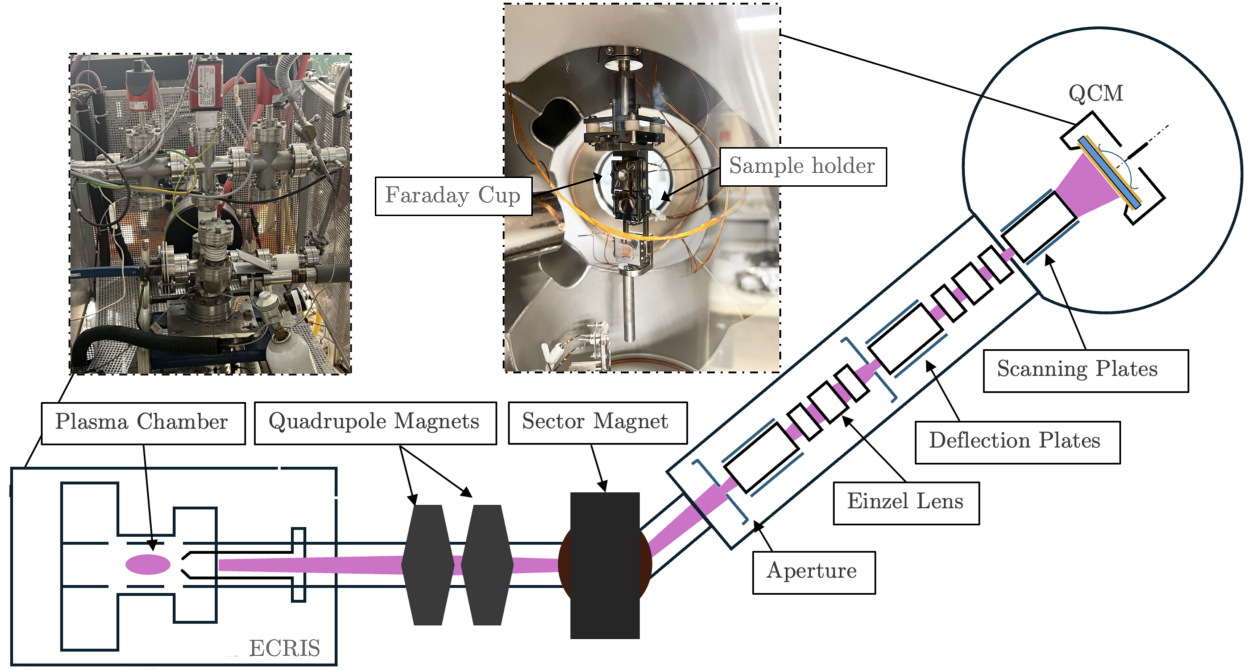


FIG. 4. Schematic layout of the TU Wien QCM measurement setup and ion beamline, including the 14.5 GHz ECR ion source, beam optics, and the QCM sample holder installed within a UHV chamber.

change is directly related to the rate of mass change on the crystal surface, even small variations in the mass of a deposited thin coating due to ion irradiation can be detected by sensitive frequency monitoring. Equation (3) is valid for coated layers with a thickness much thinner than the quartz crystal as it neglects the contribution of such layer in the total response of the system [22]. Including beam irradiation parameters in Eq. (3), the sputtering yield of the deposited layer can be obtained:

$$\mathcal{Y}(\text{atoms/ion}) = \frac{1}{\Phi A_q m_T} \frac{m_0 \Delta f}{f_0 \Delta t}, \quad (4)$$

where Φ is the ion flux density, m_T the target particle mass, and A_q the sensitive surface area of the quartz target. For this study, a layer of oxygen-free copper with a thickness of 216 nm was deposited via physical vapor deposition on the quartz crystal using magnetron sputtering. As surface roughness is a key property in sputtering yield experiments [28], atomic force microscopy (AFM) using a Cypher S (Asylum Research) microscope was employed to image nanoscale surface features and quantify the surface roughness. AFM scans over $2 \times 2 \mu\text{m}$ areas were conducted, resulting in an average surface roughness of $R_a = 3.53 \pm 0.68 \text{ nm}$. An example of surface micrographs is presented in the embedded plot of Fig. 5. The experimental setup at TU Wien employs plano-convex SC-cut quartz crystal resonator discs with a resonance frequency of 6 MHz and thickness of 0.302 mm, stabilized at a minimum of the frequency as function of temperature curve prior to

measurements [22]. Frequency measurement precision is constrained by the quartz crystal resonance drift of approximately 2 mHz/min and 5 mHz electronic noise. The quartz crystal with the deposited layer is mounted on a sample holder under ultrahigh vacuum (UHV) in the range of 10^{-9} mbar reducing surface oxidation to a minimum during ion beam exposure. The sample holder presented in Fig. 4 is equipped with a Faraday cup for beam current measurement and allows millimeter-scale displacement for beam lateral profile optimization and alignment on the active area of the quartz crystal ($\varnothing 4 \text{ mm}$). Beam intensity profiling before and after each measurement ensures that the ion current density variation is within 10% over the whole active target area and allows for the calculation of the uncertainty due to the beam intensity variations [22]. Following the adjustment of the ion beam, the quartz crystal is inserted into the beam path and the frequency change is recorded. Irradiations at TU Wien were carried out using the beamline shown in Fig. 4, equipped with the 14.5 GHz electron cyclotron resonance (ECR) ion source [29] capable of producing ions with various charge states from different gases. A sector magnet separates the ions based on their charge-to-mass ratio, whereas multiple electrostatic lenses and deflection plates guide the beam through sets of apertures. Additionally, a dedicated pair of scanning plates is used to raster the beam across the sample surface, ensuring uniform irradiation over the entire active target area. Sputtering yield measurements are performed with sample exposure to the beam at a specific tilt angle maintained for 10–20 min. For each tilt angle setpoint, a

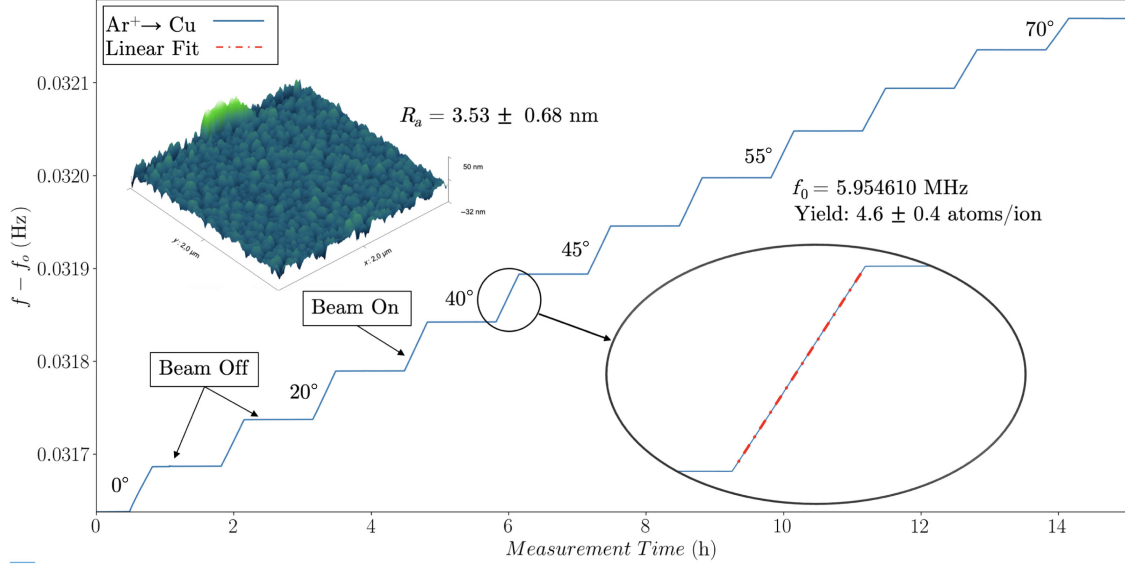


FIG. 5. Example of a QCM scan plot in the angle range of $[0^\circ\text{--}70^\circ]$ presenting the frequency shift Δf as a function of time and linear fit for sputtering yield evaluation. The beam on phases correspond to different irradiation angles with respect to the sample. The embedded plot presents a preirradiation AFM surface roughness micrograph for the sample used in this measurement campaign.

1-h beam-off period was applied both before and after irradiation to ensure thermal relaxation of the sample. Additionally, a cleaning procedure using an Ar^+ ion beam was conducted at a 60° tilt angle to remove surface contaminants and hydrocarbon residues prior to the irradiation campaign.

For this study and in order to study the sputtering yield of copper applicable to RFQ cavities under proton and ion irradiation, sputtering yield measurements with protons of 2 and 6 keV and Ar^+ at 2 keV and Ar^{6+} 36 keV ions beams were performed in an angle sweeping configuration in a range from normal incidence up to 70° . To assess the repeatability of the measurements, the 6 keV proton irradiation was performed twice, using both ascending and descending angle scan configurations.

The projected ranges of the incident protons and argon ions at these energy levels are significantly smaller than the thickness of the copper film, ensuring that all ion-induced collisions and sputtering events occur entirely within the deposited copper layer. The maximum energy of 6 keV of protons corresponds to the maximum extraction voltage available from the accelerator beamline, whereas the maximum tilt angle of 70° was selected to maintain a uniform irradiation area with respect to the projected beam spot and active target surface. The high energy range was explored using the 36 kV Ar^{6+} argon ion beam following the adjustment of the sector magnet magnetic field. Table I summarizes the conducted experiments along with the corresponding irradiation parameters. All irradiations were carried out at room temperature with achieved beam currents in the microampere (μA) range to minimize heat deposition and prevent thermal surface modification.

Figure 5 presents an example of an angle sweep measurement for the 2 keV Ar^+ irradiation case in the angle range of $[0^\circ\text{--}70^\circ]$, including the beam on/off phases. Each beam on phase corresponds to a different irradiation angle where the slope $\Delta f / \Delta t$ derived from the frequency fit and average beam flux Φ were used for the calculation of the sputtering yield ($\mathcal{Y}$) according to Eq. (4). Following the completion of irradiation (beam-off phase), thermal stress on the quartz crystal is released enabling the desorption of shallow implants diffusing to the surface. Irradiation time and beam flux were selected to ensure the equilibration of remaining implantation processes, temperature variations, and adsorbate release effects, leading to a linear trend denoting the target sputtering dominated region.

B. Experimental and simulation results

Figure 6 presents the QCM experimental results for the cases of argon (2 keV Ar^+ , 36 keV Ar^{6+}) and proton (2 keV, 6 keV) beams. The results are compared with sputtering yield calculations using the SDTrimSP [18] software and its associated graphical user interface [30]. The simulations were performed with proton and argon beams

TABLE I. Irradiation parameters for copper QCM sputtering yield measurements.

No.	Ion	Energy (keV)	Current (μA)	Fluence (ions/ cm^2)
1	Ar^+	2	1.88	1.58×10^{16}
2	Ar^{6+}	36	75.49	5.84×10^{14}
3	p	2	1.88	2.31×10^{16}
4	p	6	51.13	3.87×10^{17}

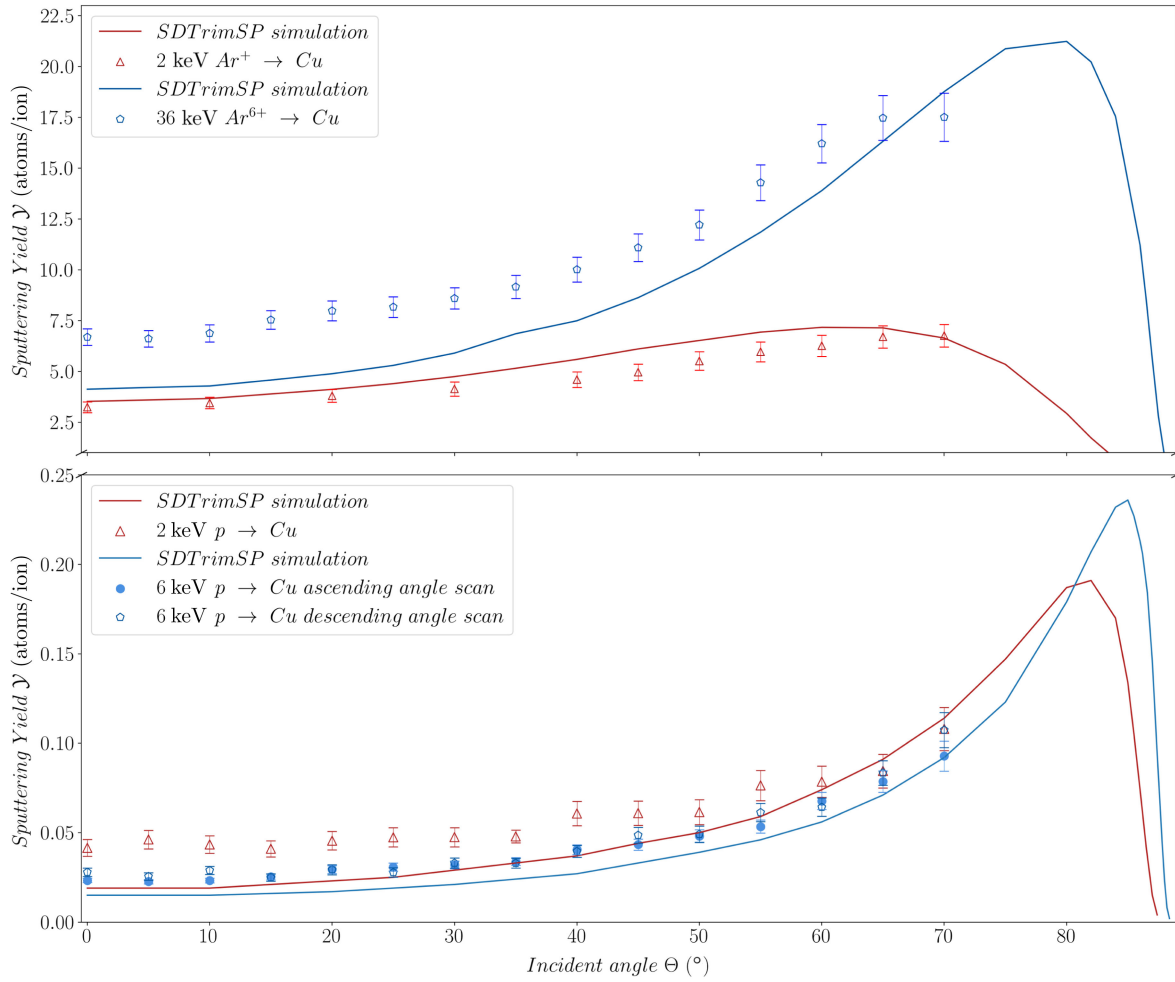


FIG. 6. Experimental and simulation results for sputtering yield of copper target with 2 keV Ar^+ , 36 keV Ar^{6+} argon beams, and 2, 6 keV proton beams.

with the respective energies composed of 10^5 particles and incidence angles in the range of $[0^\circ\text{--}89.5^\circ]$ impinging on a copper target with a thickness of $1\text{ }\mu\text{m}$. The number of particles was chosen as a trade-off between adequate statistics for the sputtering yield and computational time. Static simulations with selected default values of 3.49 eV [31] for the surface binding energy (E_{ESB}) and 19 eV for copper displacement energy (E_{DE}) were performed using the KrC interaction potential [32] and Gauss-Legendre integration method [33]. In SDTrimSP simulations, the sputtering yield is determined solely by collision cascades that reemerge at the surface and result in the displacement of surface atoms therefore and preliminary simulations with different targets led to the estimation of optimal simulation thickness. Regarding the experimental results, transient effects such as ion source current drift, changes in surface roughness during irradiation and temperature changes could lead to a QCM resonance frequency drift and could introduce systematic uncertainties in the measurements. Therefore, the error bars for the experimental results presented in Fig. 6 are calculated using the uncertainties

in ion beam flux, Faraday cup measurements, and frequency linear fit uncertainty. The average experimental uncertainty was estimated at 7.2% for argon and 8.8% for proton irradiations, respectively.

In all studied cases the sputtering yield is increasing monotonically with increasing angle of incidence up to a maximum angle and then decreases followed by large values of reflection coefficient. The angle of the sputtering yield maximum is lower for the case of Ar^+ , Ar^{6+} ions compared to protons and is shifted to larger values with increasing projectile energy. The angular dependence of the sputtering yield stems from the near-surface nature of recoil cascades that result in target atom ejection [4,34]. At higher incidence angles, reduced implantation depth shifts the energy deposition closer to the surface, enhancing sputtering both for protons and heavy ions. Additionally, results indicated that in the case of argon ions the sputtering yield increases with higher energies in contrast to protons, which exhibit the opposite trend. The difference in sputtering yield values arises from the distinct masses of the projectiles and their interaction mechanisms with target atoms. As

the ion energy increases, projectiles penetrate deeper into the material, reducing the possibility of surface-reaching recoil cascades. However, higher energies also increase the probability of energetic interactions increasing the sputtering yield. In the energy range of interest (1–120 keV) the dominant energy loss mechanism of protons is electronic stopping, whereas for heavy ions nuclear stopping dominates [4,35].

For both proton and argon beams, the experimental results show a reasonable level of agreement with the simulations. The study of sputtering yield of proton and Ar ion beams of different energies on copper targets is well documented in literature and thorough reviews include the works of Behrisch and Eckstein [35] and Oechsner [36]. Although a direct comparison is challenging due to the scattered nature of available data across different energies and angles, as well as the limited number of comprehensive angular scans. Comparison of results is further complicated by the different experimental conditions, particularly variations in sample purity, surface roughness, contamination levels, and vacuum quality. Taking these factors into account, the results show a reasonable level of agreement with previously reported data for Ar ion bombardment of polycrystalline Cu targets under normal and oblique incidence angles [35–40]. These findings are consistent with interpolated values based on the $\mathcal{Y}(E)$ dependence described by Sigmund's theory [15], as well as with the energy and angle-dependent fit formulas proposed by Eckstein and Preuss [41]. For the case of argon beams, these studies consistently report higher experimental sputtering yields in the keV energy range compared to the values predicted by the fitted models used in [35]. A similar trend is also observed in our study, where the results are closer to the experimental values reported by other authors compared to SDTrimSP simulation results. Similarly, for the case of protons, the measurements are consistent with previously reported data for copper targets bombarded by protons and reported in [42–46]. Also for this case, the experimental results of our study are consistently higher than the corresponding simulation results, an effect also noted in [35] and show better agreement with the experimental data from [43–45] compared to simulated values. For both argon and proton beams, the results of our study compared to literature, validate the underestimation of sputtering yield from the simulations at lower incidence angles, while better agreement with experimental results is observed at higher angles. Behrisch and Eckstein [35] attribute this general tendency on copper targets to issues with the selected interaction potential (KrC), surface binding energy values, inelastic energy loss as well as the occurrence of collisional spikes. The discrepancy observed between SDTrimSP results and the experimental data of our study could be linked to the surface roughness and morphology of the sample as well as the selected surface binding energy,

approximated by the heat of sublimation [35]. The repetition of simulations using the SDTrimSP dynamic calculation method that allows target surface composition evolution under ion irradiation, led to deviations of less than 2% in sputtering yield values in the selected QCM experimental fluence range (10^{14} – 10^{18} ions/cm²) as expected for mono-elemental targets [47].

IV. RFQ ELECTRODE SPUTTERING YIELD AND EROSION RATE

Following the methodology presented in Sec. II A, the ion energy and incidence angle distributions were used for the estimation of sputtering yield for the ions impinging on the RFQ copper vanes. A set of SDTrimSP simulations for proton and argon ions (300 simulations per case) covering an energy range of 2–120 keV and incidence angles from 0° to 89.6° were performed with higher angular resolution at larger angles to capture the increasing sensitivity of sputtering yield in that regime.

Simulations were performed with the experimentally validated parameters described in Sec. III B that provide improved agreement with experimental results in the angle range of interest and the resulting sputtering yield values were interpolated using piecewise cubic Hermite polynomials across both energy and angle data points. The interpolated results are presented in Fig. 7(a) for protons and in Fig. 7(b) for argon ions confirming the trends observed with increasing energies and angles in the simulations performed and reported in Sec. III B. For protons, only the angular range from 40° to 89.5° is presented as sputtering yields below 40° were negligible. Using the interpolated datasets and by applying binning in both energy and incidence angles the sputtering yield for the lost particle distributions is evaluated. Particles with energies exceeding 130 keV were excluded from the analysis due to reduced possibility of losses beyond this energy threshold. Although the ESS RFQ is designed for proton acceleration, the same particle loss distribution was applied to the argon case enabling a comparative analysis of sputtering behavior under heavy-ion acceleration conditions.

Histograms presented in Fig. 8(a) for protons and (b) for argon ions summarize the sputtering yield calculated values based on grouped lost particles data by energy and incidence angles. Finally, the sputtering yield results, shown in Figs. 9(a) and 9(b) as a function of binning vane angle α , indicate that sputtering yield levels and subsequent surface erosion in the RFQ electrodes are nonuniform and concentrated near the vane tips.

These calculated parameters as a function of vane angle α can be used to estimate the vane erosion rate, δ_{da} , expressed in $\mu\text{m}/\text{year}$ using an angular bin of $d\alpha = 5^\circ$ employing the simplified cylinder approximated vane geometry:

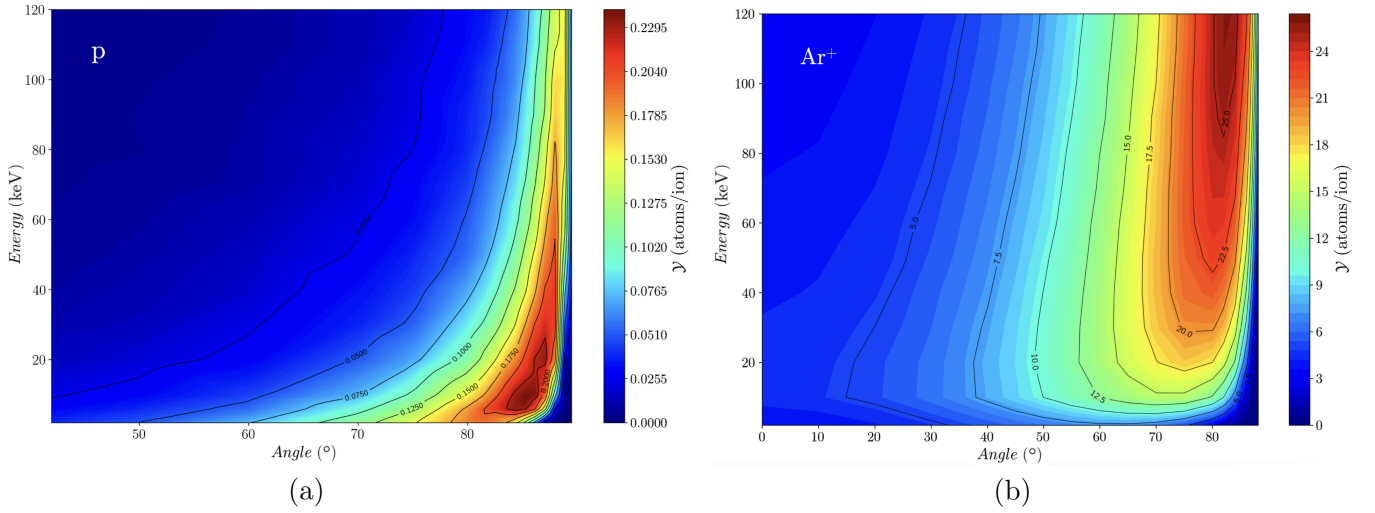


FIG. 7. SDTrimSP calculated sputtering yield $\mathcal{Y}$ of Cu target bombarded with protons (a) and argon ions (b) as a function of energy and incidence angle.

$$\delta_{d\alpha} = \frac{I' f(\alpha) \bar{Y}_{p,Cu}(\alpha)}{d_{Cu} \frac{\pi}{180} d\alpha p L} T, \quad (5)$$

where I' is the ion beam modified current taking into consideration the ESS beam properties normalized for the amount of lost particles and equal to $I'_p = cNIwf$ with units given in incident ions/s. In this quantity, I (62.5 mA)

is the peak proton beam current, w (2.86 ms) the beam pulse length, f (14 Hz) the repetition rate as derived from ESS design parameters [1], c a rescaling factor for selected total loss percentage at the selected cavity area, and N represents the number of ions per coulomb of electric charge. The form of Eq. (5) indicates that RFQ operation mode (pulsed or cw) affects significantly the calculated

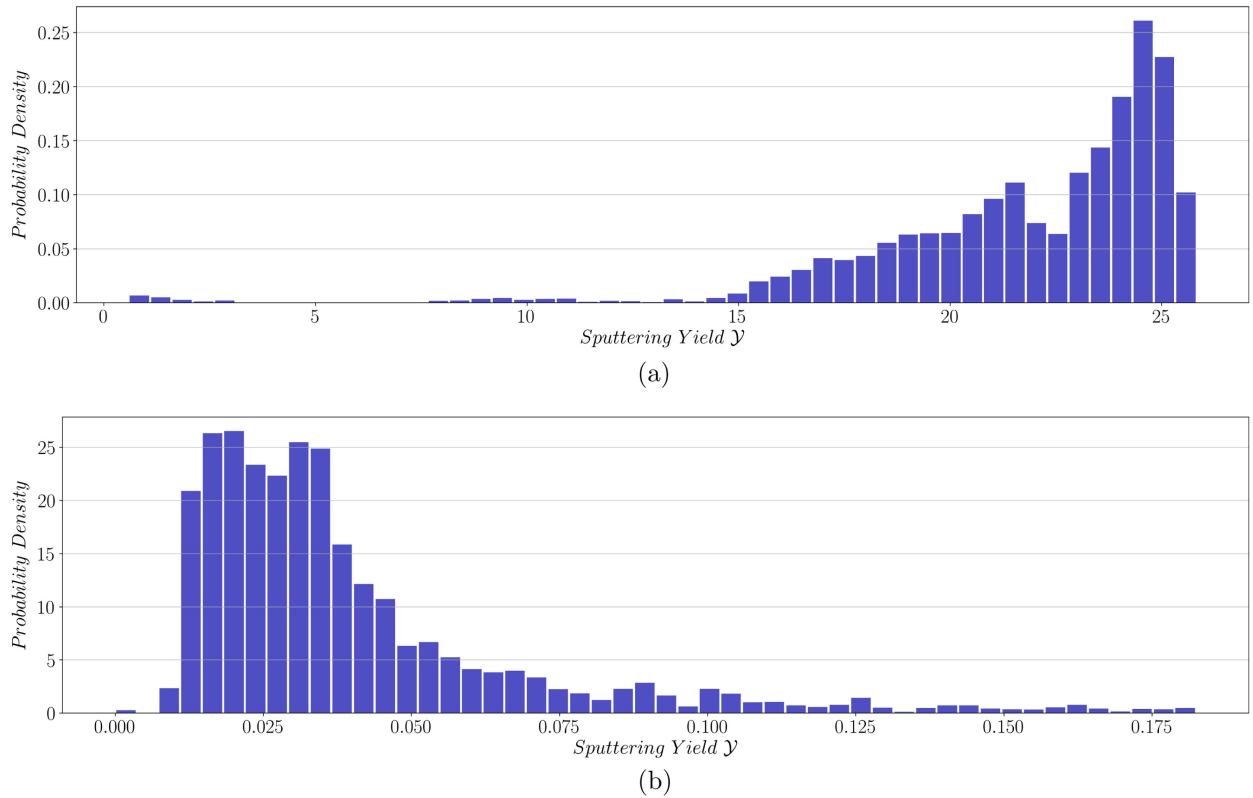


FIG. 8. 1D probability density function histograms of sputtering yields for (a) protons and (b) argon ions, based on grouped lost particle data by energy and incidence angle.

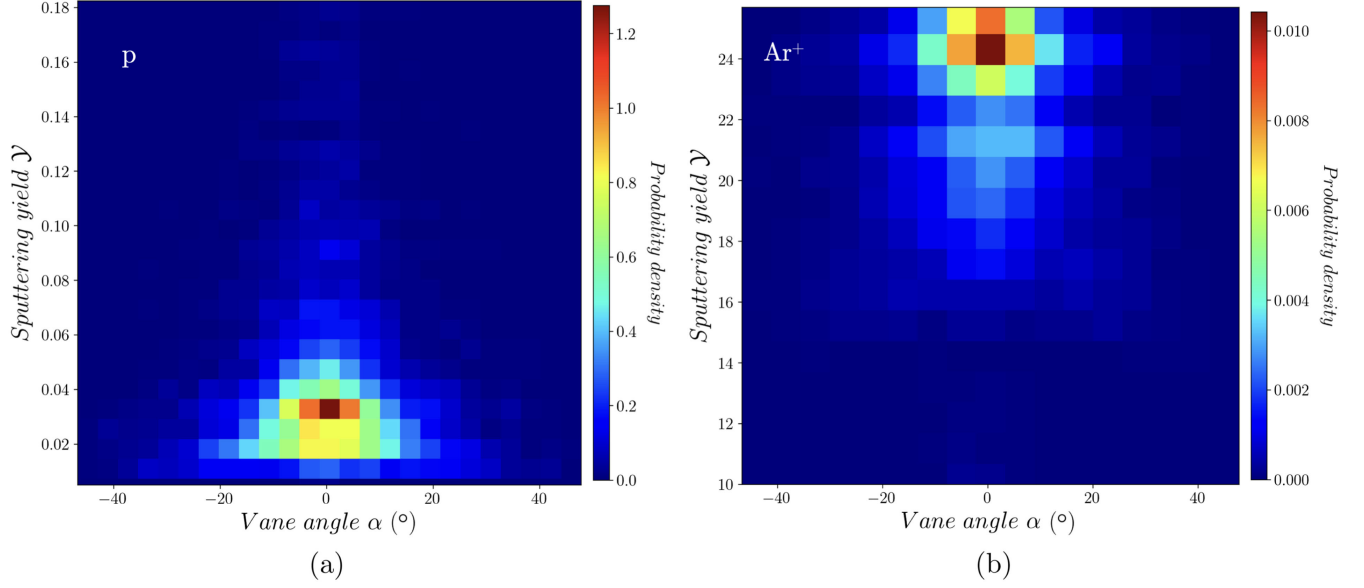


FIG. 9. Sputtering yield values for the RFQ lost particles for all four RFQ electrodes as a function of vane angle α for proton (a) and argon ion (b) irradiation.

values leading to greater erosion rates for higher losses, high current, or cw cavities. The modified current I' is multiplied by the probability density function $f(\alpha)$ corresponding to each vane derived from the histograms in Fig. 3 and average projectile sputtering yield $\bar{Y}_{p,Cu}$ determined for

selected angular bins of $d\alpha = 5^\circ$. In addition, T represents a temporal scaling (s/year) factor, enabling the calculation of the annual erosion rates.

The calculated quantity in the numerator of Eq. (5) needs to be divided by the copper density d_{Cu} in atoms/m³ multiplied by the vane area A (embedded plot in Fig. 10)

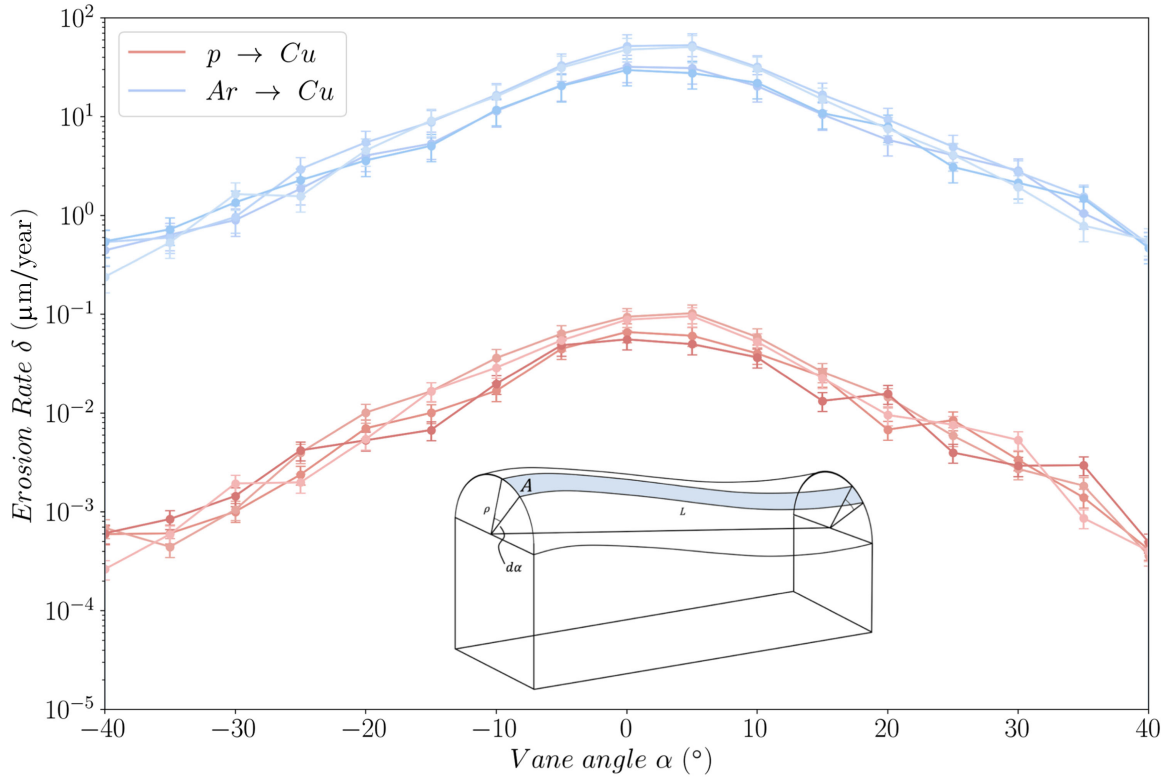


FIG. 10. Erosion rate calculated for the four RFQ vanes in case of protons (red curve set) and argon ions (blue curve set). The embedded plot presents the defined vane surface area A , used for the calculation of erosion rate.

assuming a simplified cylinder arc geometry, where $\rho = 3$ mm is the radius, $L = 2$ m the approximated RFQ length where the losses are concentrated (taking into consideration only the *shaper* and *gentle buncher* sections of the cavity) and $d\alpha$ the minimum bin width. Equation (5) estimates the erosion rate in the axial direction of a cylinder and can be tailored to specific RFQ regions by the adjustment of surface area A and modified current I' . The results presented in Fig. 10, plotted on a logarithmic scale, show the erosion rates for all four vanes as a function of the vane angle α for both protons (red curve set) and argon ions (blue curve set). The data indicate significantly higher erosion rates for argon, reaching up to 53 $\mu\text{m}/\text{year}$ even when using the ESS proton beam parameters (4% duty cycle). In contrast, proton-induced erosion is significantly lower, with peak values not exceeding 0.1 $\mu\text{m}/\text{year}$. As discussed in Sec. III B, the comparison between the QCM experimental results and existing literature leads to observed differences between measured and simulated sputtering yields at the corresponding energy and angular ranges. These differences contribute to an estimated uncertainty of 20% for protons and 30% for argon ions in the calculated sputtering yields and erosion rates. The error bars reported in Fig. 10 reflect the combined uncertainty from both the QCM measurement errors and the expected uncertainty between experimental and simulation results.

V. DISCUSSION

A. Functional RFQ stability due to electrode erosion

The analysis presented in this study is particularly relevant for RFQ cavities designed for acceleration of heavier ion species [5,6,48–50] and high-duty cycle or cw configurations. The erosion rate can be incorporated into the perturbative model of the RFQ cavity to evaluate both the frequency shift and the resulting voltage perturbation. This approach is motivated by the fact that modifications to the RFQ electrode geometry, particularly at the vane tips, directly impact the resonant frequency and the voltage distribution within the cavity due to the nonuniform nature of erosion rates [12]. The formulation of the perturbation problem on RFQ resonant cavities dictates that the pole-tip region is significantly more sensitive to geometric deviations compared to the other parts of the cavity [12,51]. As a result, maintaining tight control over the intervane voltage and geometric tolerances is essential, with permitted deviations typically restricted to within a few percent during the design phase [51]. Starting from a small variation of the vane tip radius ρ by an amount $\Delta\rho$ and a subsequent surface perturbation ΔS , the geometry changes in the electric field dominated region of the cavity can be considered as a capacitance perturbation. Under these conditions, the frequency shift can be described using a simplified form of Slater's theorem [2,12]:

$$\Delta f = f \frac{\epsilon_0 |E|^2 \Delta S}{4u_{\text{em}}}, \quad (6)$$

where f is the fundamental cavity frequency, ΔS the surface perturbation, u_{em} the electromagnetic energy density per unit length, and E the average electric field in the affected region. All these quantities can be obtained from E/M simulation codes such as SUPERFISH [52]. In the context of this analysis, the surface perturbation ΔS can be calculated as a function of the average vane angle $\bar{\alpha}$ and average erosion rate $\bar{\delta}_{d\alpha}$ as derived from Fig. 10:

$$\Delta S = 2\rho \sin \bar{\alpha} \bar{\delta}_{d\alpha}. \quad (7)$$

The final form of Eq. (6) indicates that even small variations on the order of tens of micrometres on the vane surfaces can induce substantial frequency shifts and detuning, reaching tens to hundreds of kilohertz. Therefore, the effect of electrode sputtering is highly relevant for RFQs with the exception of those primarily designed for proton or H^- acceleration where the impact is negligible. Currently, most high-current cw RFQs are primarily designed for proton or H^- acceleration (e.g., LANL LEDA [53], CEA IPHI [54] projects), while heavy-ion RFQs (e.g., CERN Linac3 [55], MSU FRIB [56], GSI HLI [57]) are mainly designed for low-current operation, thus potentially mitigating the impact of electrode sputtering or deferring the appearance of severe erosion. Accounting for sputtering effects can enhance the long-term operational stability of the existing facilities and should be explicitly considered in the design of emerging high-current cw ion accelerators, both for light and heavy ions (e.g., IFMIF EVEDA [58]). Additionally, as the erosion rate varies along different RFQ sections, the resulting perturbation will lead not only to frequency shifts but also to voltage instabilities increasing the breakdown rate and degrading transmission and longitudinal beam emittance. Mitigation measures to compensate for these effects are case dependent and may include the implementation of separate cooling circuits for localized perturbation retuning of individual RFQ sections, as well as adjustments to the low-level rf system. More disruptive actions include the retuning of the RFQ structure using adjustable tuners, the replacing of eroded electrodes and RFQ modules or redesigning the linac for higher injection energies that are expected to significantly reduce the erosion rates. However, the resulting frequency shifts may exceed the compensation capability of standard tuning mechanisms [59] leading to substantial redesign efforts and extended maintenance periods.

B. Applicability of the analysis to RFQ cavities

Following the results presented in the previous sections of this manuscript, certain points and assumptions require further consideration in order to assess their impact on the sputtering yield results and, consequently, the applicability

of this analysis to real-world RFQ cavities. A key consideration is the difference in crystallinity between actual RFQ copper and the QCM polycrystal deposited copper layer. Sputtering results for polycrystalline targets, such as RFQ copper, may deviate significantly from both simulation results (based on amorphous target models) and experimental data obtained from single-crystal targets with specific orientations. In polycrystalline materials, sputtering behavior is influenced by the underlying lattice structure, including effects such as preferential sputtering and channeling, which depend on the crystal orientation [60,61]. These effects can lead to pronounced sputtering yield minima, particularly along close-packed crystallographic directions [35,60,62,63]. EBSD analysis on ESS RFQ copper samples indicated heavily twined grains with average grain size (equivalent circular diameter) of ≈ 220 μm and no preferred crystal orientation [64]. Despite the fact that individual grains are expected to contribute differently to the sputtering yield [35], this variation is effectively compensated due to the observed random orientation and statistical averaging over a large RFQ area affected by the beam losses. Furthermore, surface roughness plays a significant role in sputtering yield results and subsequent erosion rate, a topic addressed in several dedicated studies [28,65,66]. The measurements of this study were performed under controlled surface conditions with a roughness of $R_a \approx 4$ nm significantly lower than RFQ electrode roughness design requirements ($R_a < 0.4$ μm) [13,67]. Postirradiation AFM analysis confirmed that the variation of QCM target roughness due to sputtering at those fluence levels was negligible. Despite the fact that surface roughness is further improved during RFQ rf conditioning, phenomena such as blistering [68], electrical breakdown craters [8], ion trapping, implantation, and radiation damage [9] further affect surface topology and consequently influence the sputtering yield [35]. The complex surface interactions signify the need for detailed surface modeling and characterization of real RFQ copper samples. Simulation tools like TRI3DYN [69] and SDTrimSP-3D [70] can be used to incorporate dynamic surface evolution, including changes in electrode composition during nominal operation resulting in more realistic simulation of RFQ surface conditions using microscopy images as direct inputs. The use of such 3D simulation codes in recent studies [28,71] led to the conclusion that enhanced surface roughness leads to lower sputtering yield values affecting the angular emission distribution of the sputtered atoms. During the incidence of a particle on a surface with increased roughness, the incidence angle Θ is affected by different features of the surface morphology, such as nanostructures or protrusions leading to the effects of geometrical shadowing, trapping of sputtered atoms, and increased redeposition possibility [71]. As an example, Stadlmayr *et al.* in their recent study on He-induced nanostructured tungsten (W-fuzz) found that a nanostructured surface leads to increased redeposition rates and reduced sputtering yield compared to flat targets [71].

Nevertheless, this study proposes an analysis that provides a baseline understanding of sputtering yield mechanisms in the context of RFQ cavities, serving as a reference point to interpret and compare more complex, real-world electrode surfaces. In addition, it is important to consider that the present study assumes a well-matched beam with optimized parameters, maximizing transmission through the RFQ and minimizing particle losses. As a result, the analysis reflects ideal operating conditions and does not account for scenarios involving increased losses due to suboptimal beam tuning during commissioning, nominal operation, or interlock events that could result in complete beam loss within the cavity.

Sputtering yield results could also be affected by elevated temperatures [35,62,72]. Windawi *et al.* [62], in their study, observed temperature-dependent variations in sputtering yield during argon ion irradiation of copper targets. In the ESS RFQ cavity, thermal expansion caused by rf power losses and beam-induced heating is mitigated through a system of independent water-cooling circuits. Thermal simulations conducted during the cavity design phase estimated a temperature rise of approximately 4°C on the vane tips during nominal operation [73]. For this reason, the QCM experiments were conducted at room temperature to replicate nominal operation, although this approach does not account for transient beam events that could induce significant localized heating and surface topology modification. Finally, this analysis assumes uniform electrode erosion along the RFQ structure while neglecting activation and losses at the high-energy end. In reality, electrode erosion is nonuniform due to localized beam losses and variations in cavity geometry due to manufacturing errors further exacerbating the effects of frequency and voltage perturbations.

VI. SUMMARY AND CONCLUSIONS

The analysis presented in this study underlines the importance of sputtering and its impact on operational stability and performance of RFQ cavities. In this work, a combined experimental and simulation framework was developed with the aim to assess the erosion rates on RFQ electrodes using the ESS RFQ as a proof of principle. Particle tracking simulations for the derivation of beam loss distributions during nominal operation were coupled with BCA beam-target interaction simulations for the estimation of sputtering yield. QCM-based sputtering yield measurements were used to validate and benchmark the simulation framework across a range of energies and incidence angles using proton and argon (Ar^+ , Ar^{6+}) ion beams. The results provide a detailed spatial distribution of the sputtering yield and indicate a peak erosion rate of approximately 53 $\mu\text{m}/\text{year}$ localized on the vane tips for the case of argon ions. On the contrary, peak erosion rate due to proton irradiation was limited to less than 0.1 $\mu\text{m}/\text{year}$ using the ESS beam parameters. The findings of this analysis emphasize the increased sputtering yield and erosion rate

in high-duty cycle or cw high-power RFQs used for the acceleration of light and heavy ions. Erosion rates could lead to significant frequency shifts in RFQ cavities, potentially affecting field symmetry and accelerating voltage stability. These effects are particularly critical in accelerators with stringent operational requirements and long lifetimes and should be taken into consideration in the design of the next generation high power and intensity RFQ cavities.

DATA AVAILABILITY

The data are not publicly available. The data are available from the authors upon reasonable request.

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