Study of gas cluster ion beam surface treatments for mitigating RF breakdown

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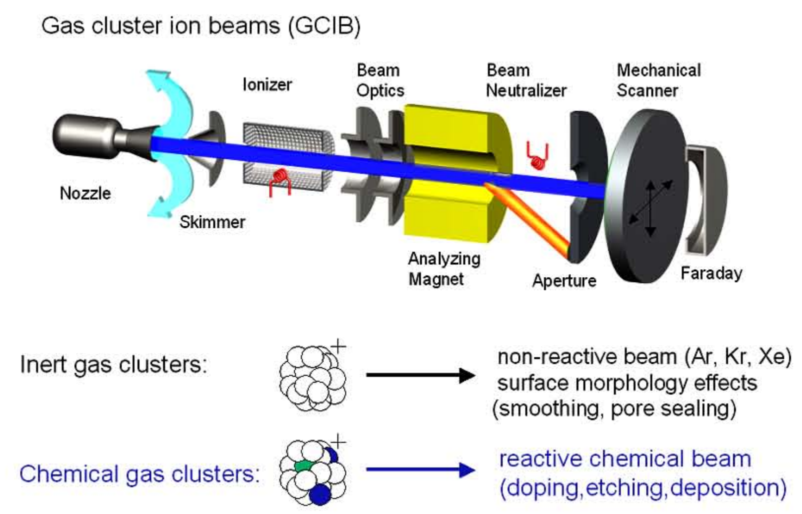
Summary

Reaching higher gradients in SRF cavities has required ever more stringent surface preparation. We are investigating surface processing with high-energy Gas Cluster Ion Beams (GCIB), a new technology that achieves an atomic level of smoothness on planar and non-planar surfaces, to increase the RF breakdown limits of RF cavities and electrodes. GCIB smoothing of Nb, Cu, Stainless Steel and Ti electrode materials have been tested using beams of Ar, Ar+H_2, O_2, N_2, Ar+CH_4, or O_2+NF_3 clusters with accelerating potentials up to 35 kV. Smoothing effects were evaluated using SEM and AFM imaging, hardening was measured using a nano indenter, and oxide thickness was determined with XPS. Fourier analysis of the AFM images shows that smoothing effects extend from atomic levels up to 2 μm. High energy Ar GCIB removed an isolated asperity on Cu that was 35 nm high and 350 nm across, and greatly attenuated 200 nm wide polishing scratch marks on Stainless Steel and Ti. Etching using chemically active clusters like NF_3, reduces the grain structure of Nb used for SRF cavities. The field emission of a GCIB processed photocathode was a factor of 10^6 less than an untreated photocathode.



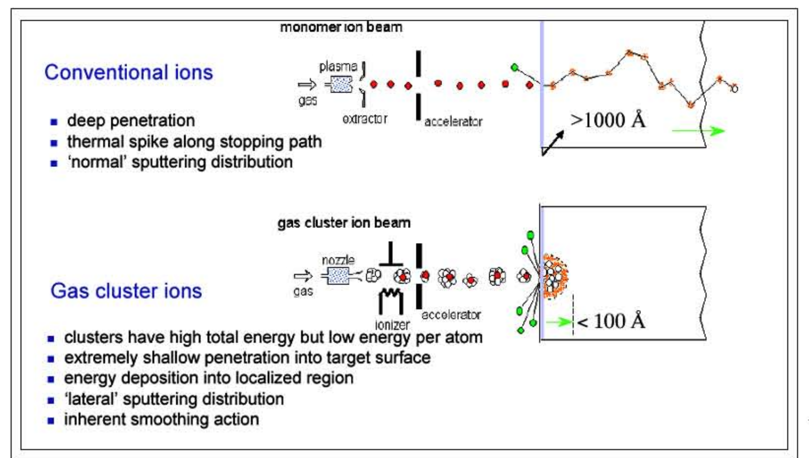
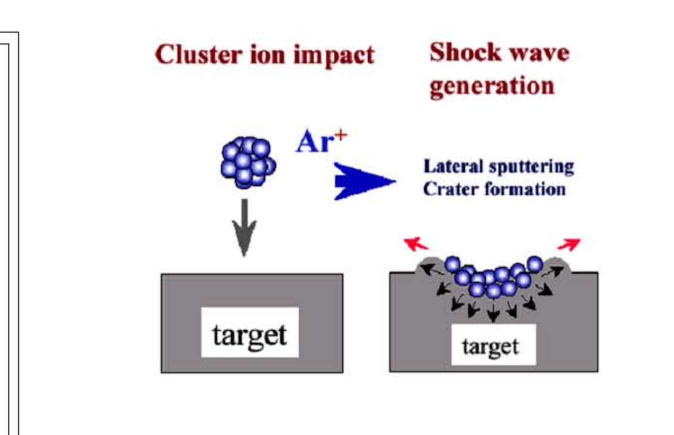


Fig. 4 Comparison of cluster ion impact with monomer ion impact on a surface



Cluster impact showing shock wave formation (Z. Insepov)

Fig. 44 Epion UltraSmoother™

Fig. 45 Phoenix GCIB Test Stand

Nb SRF samples, Cornell University – Grain removal[1]

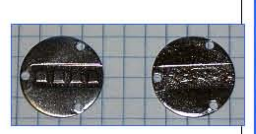


Fig. 7 Nb samples (25 mm diameter)

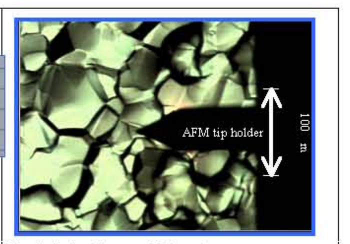


Fig. 8 Optical image of Nb surface

Fig. 9 SEM image of 700x700 μm area of unprocessed Nb (Cornell University)

Fig. 10 SEM image of 700x700 μm area of Nb processed with aggressive etch chemistry (Cornell University)

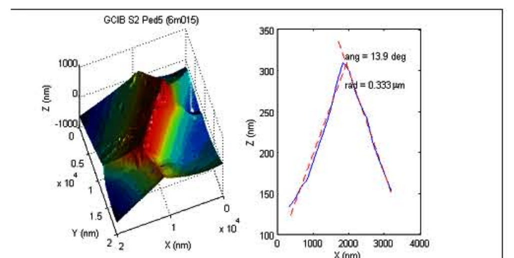


Fig. 11 Sample of AFM measurement of grain boundary angle with mathematical fit to the angle and radius (Cornell University).

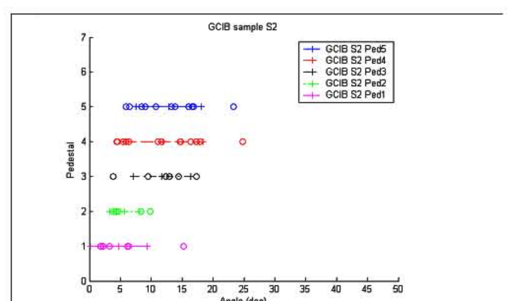


Fig. 12 Summary of AFM measurements of grain edge angle for various GCIB processes (Cornell University). The plotted angle is the deviation from a flat surface which would have an angle of 0.

Pedestal - treatment	Mean angle (degrees)	Std Dev angle	Mean radius (μm)	Std Dev radius	# meas taken
1 - NF_3 in O_2	4.82	4.60	3.38	3.20	8
2 - high energy Ar and Ar+ CH_4	5.65	2.41	1.43	0.96	8
3 – high energy Ar and Ar+ H_2	11.75	4.65	5.06	5.02	6
4 - high energy Ar	11.97	6.37	2.88	2.61	13
5 - unprocessed	12.80	5.29	2.71	3.50	12

Fig. 13 Summary of AFM measurements of grain angle and radius of curvature (Cornell University)

OFE Cu samples, SLAC – Asperity removal[2]

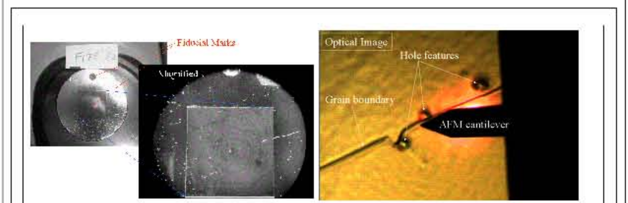


Fig. 14 OFE Cu sample showing 1x1 cm pedestal

Fig. 15 Crack on the Cu surface

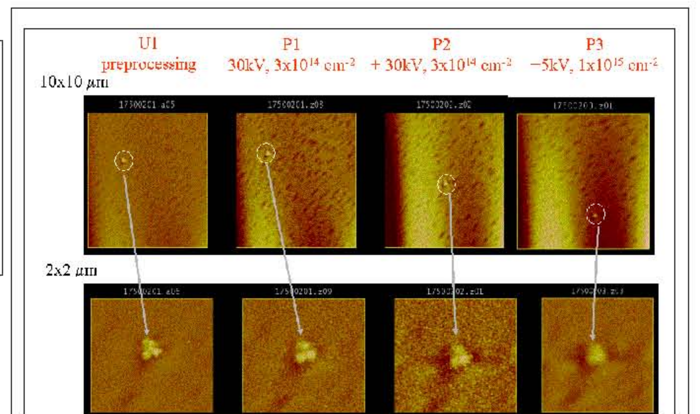


Fig. 16 Time resolved images of GCIB processing of Cu surface. The upper row of images of 10x10 μm and the bottom row are corresponding 2x2 μm images. GCIB processing proceeded in three steps as noted.

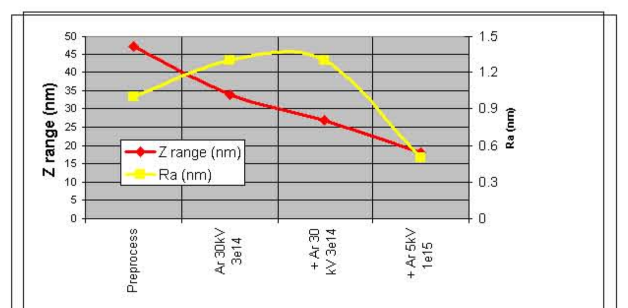
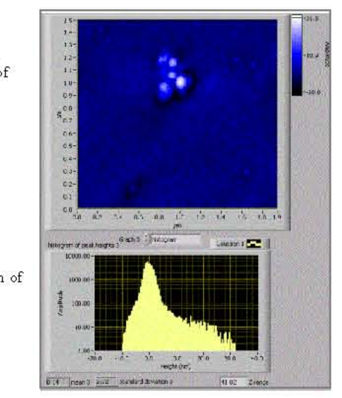


Fig. 17 The effect of GCIB processing on Z range (maximum – minimum height) and Ra (average deviation from the mean) for the AFM data of Fig. 16.

2x2 μm image of etching



Histogram of etch (nm)

Stainless Steel Photocathode, Cornell University – smoothing, hardening, oxidizing

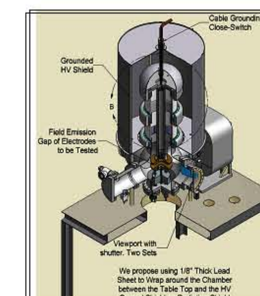


Fig. 19 Jefferson Lab Field emission test stand (A similar test stand will be commissioned at Cornell)

Fig. 20 Stainless steel photocathode. The sample was masked into 4 quadrants which received different processing.

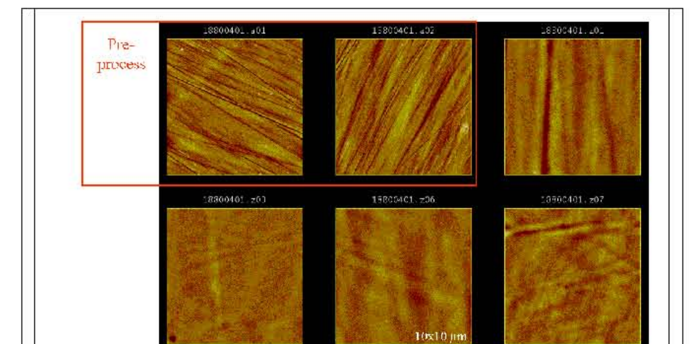


Fig. 21 Pre and post process images of Stainless steel electrodes. (Scans are 20x20 μm except as note)

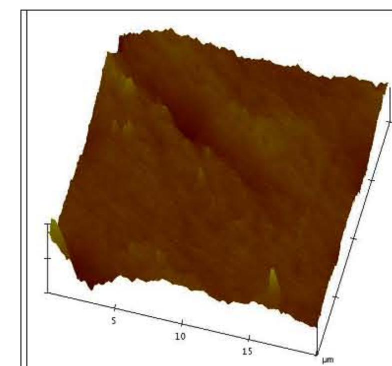


Fig. 22 A 20x20 μm area on unprocessed Stainless Steel photocathode

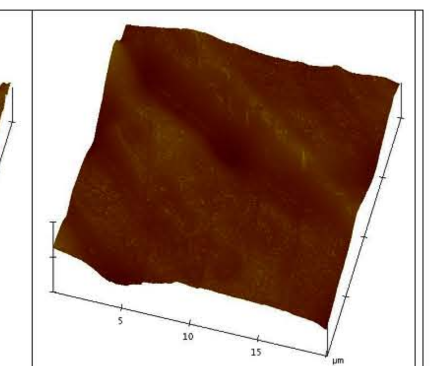


Fig. 23 The same area after processing with high energy and low energy Ar GCIB.

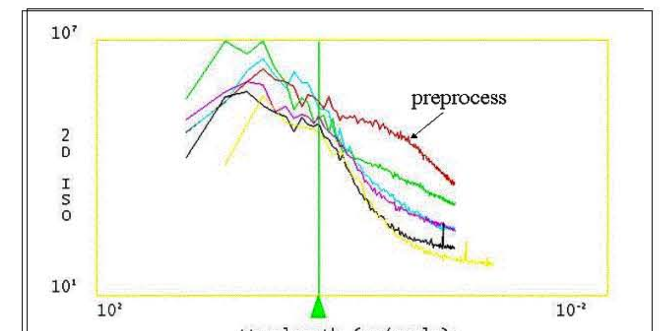


Fig. 24 Fourier analysis of AFM measurements of surface roughness for unprocessed (brown trace) and processed surfaces. Plotted are two dimensional isotropic PSD spectra. Note that the scales are logarithmic.

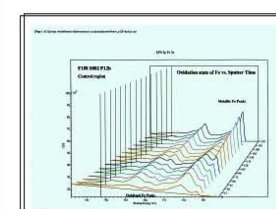


Fig. 25 XPS spectrum of unprocessed Stainless Steel.

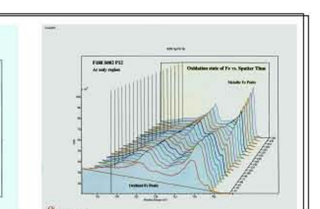


Fig. 26 XPS spectrum of stainless steel process with only Ar clusters.

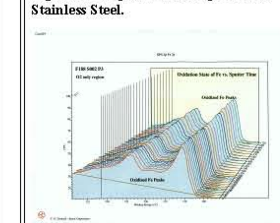


Fig. 27 XPS spectrum of stainless steel processed with only O2 clusters.

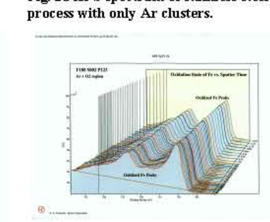


Fig. 28 XPS spectrum of stainless steel processed with Ar and then O2 clusters.

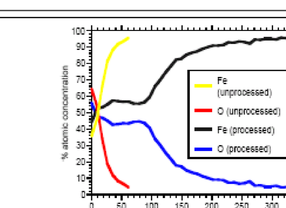


Fig. 29 XPS Depth profile of Fe and O atomic concentration for unprocessed and processed Stainless steel (T. Tetreault of Epion, L. Scudiero of Wash. State Un.)

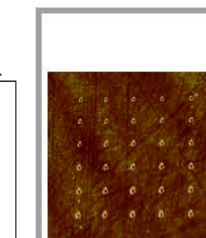


Fig. 30 Example of nano indenter data. An AFM measurement of the impressions.

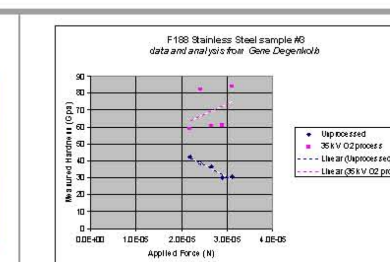


Fig. 31 Summary of several AFM measurements of the depth of the impressions as a function of the applied force on the diamond tip for unprocessed and processed stainless steel.

Possible GCIB applications for SRF cavities

- Etching
  - flattening grain structure
- Smoothing
  - Asperity removal, atomic smoothing
- Cleaning
  - Final cleaning, desorbing gasses
- Surface chemistry
  - Reduce or increase oxide thickness
  - Hardening
  - Depositing layers

In-situ GCIB processing

- GCIB is performed in high vacuum
- Can be used as the last conditioning step after all etching, washing, baking operations
- If a problem area is identified during RF testing, GCIB processing can be reapplied to that location without breaking vacuum

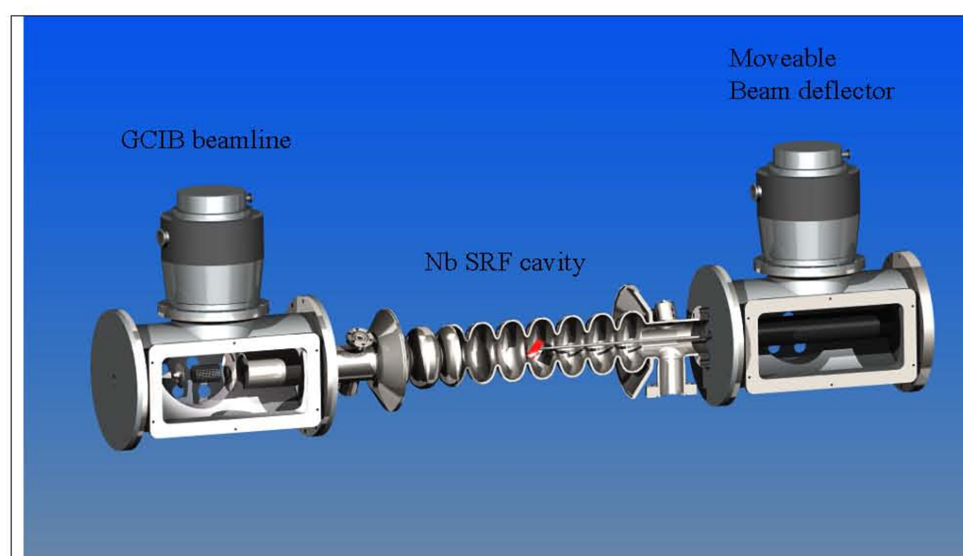


Fig. 33 Conception of an Epion product for in-situ smoothing of the inside of an RF cavity. (SRF cavity model courtesy of Fermilab).

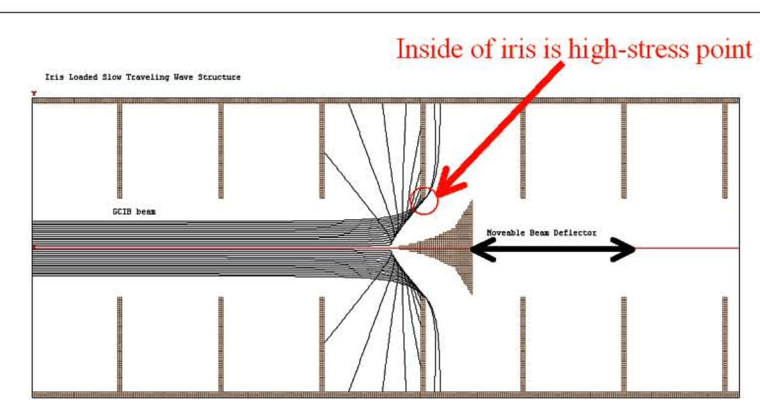


Fig. 6 In-situ processing of an RF Cavity with GCIB. A numerical simulation of trajectories of a GCIB beam deflected to process the high electrical stress points at the inner radius of the irises.. Both the position and the voltage on the deflector can be changed to allow processing of the important surfaces.

First High voltage test of a GCIB treated electrode

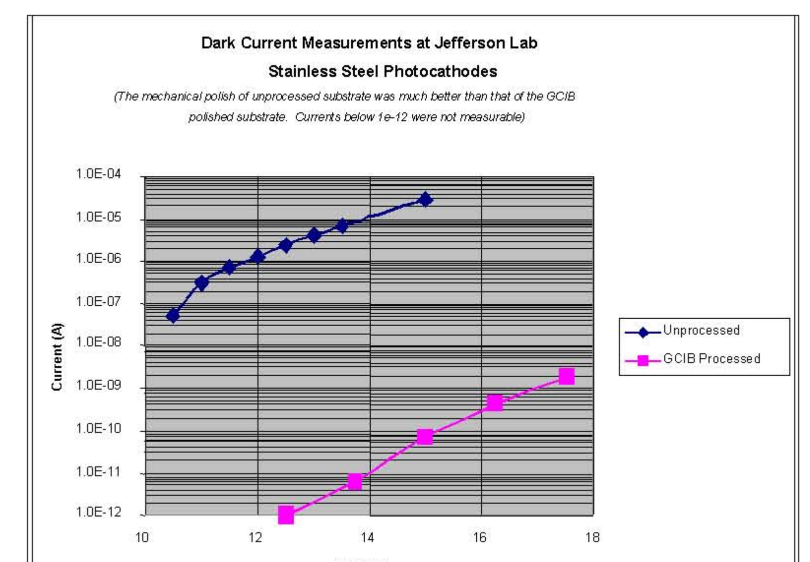


Fig. 32 The first HV test of a GCIB treated electrode. Field emission current as a function of electric field strength for a unprocessed and GCIB processed photocathode. Both measurements were made under identical conditions on the same test stand. (C.K. Sinclair, Private communication)

[1] J.E. Shipman, G. Werner, private communication

[2] "Smoothing RF cavities with gas cluster ions to mitigate high voltage breakdown", D.R. Swenson, E. Degenkolb, Z. Insepov, L. Laurent, G. Scheitrum, accepted by Nucl. Instrum. Meth. in Phys. Res. B (proceedings of CAARI 2004)