ENERGETIC CONDENSATION GROWTH OF THINFILMS FOR FUTURE SRF ACCELERATORS *

Presented by

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at

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Acknowledgments

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Outline

- Alameda Applied Sciences Corporation: an Introduction
- Phase II Project Goals
- Relevance to NP Programs
- Current Status of Project
- Future Plans

Alameda Applied Sciences Corporation

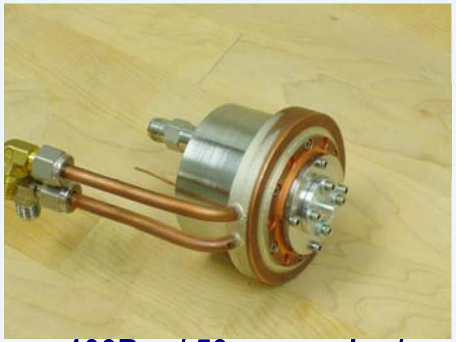
Superconducting Thin Films

RRR ~300, T_c =9.27K

Pulsed Neutron Source

2.5 and 14 MeV neutrons

Fast Gas Valve



100Bar / 50μs opening/ <500μs closing

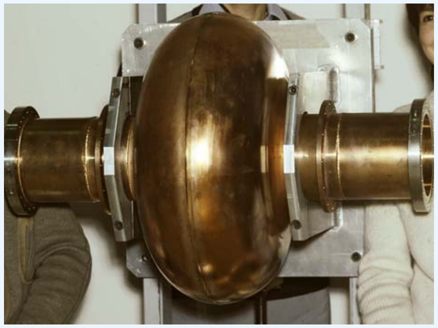
Diamond Radiation Detectors

UV and soft x-ray

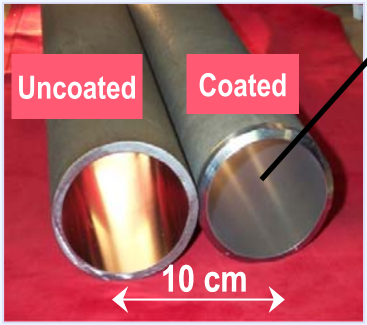
≤ 15 keV

- Founded in 1994, privately held CA Corporation
- 8 employees, ~$1.5 million 2010 revenue
- Develop/license IP via contract R&D
- Three Pre-commercial areas:
  - Cathodic arc coatings CED™
  - Fast pulsed neutron sources for WMD and HE detection
  - Fast Supersonic Gas Valves

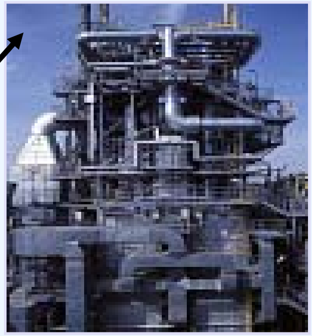
Cathodic Arc Coatings (CED™)



CED™ coating of Cu cavities for SRF



Anti-coking coating on furnace tube



Benefit: extended interval between de-cokings

Phase II Tasks and Schedule

- Coat pure Nb films on a-sapphire and Cu substrates using the CED™ coater (year I)
  - Measure the thin films (AASC and JLab and NSU)
- Coat pure Nb films on a-sapphire and Cu in the CAD chamber (year I)
  - (the CAD chamber was used in Ph-I to produce the Nb_3Sn films)
  - Measure the thin films (JLab and NSU)
- Coat Nb_3Sn on a-plane sapphire in CAD chamber (year II)
  - Measure the thin films (AASC and JLab and NSU)
- Coat the thin films using pulsed biased CAD (AASC) (year II)
  - Measure the thin films (AASC and JLab and NSU)
- Coat Nb_3Sn on Nb and/or Cu in CAD chamber (year II)
  - Measure the RF properties in the SIC facility (JLab)

Motivation

- More than 10000 particle accelerators worldwide; most use *normal* cavities
- Facility for Rare Isotope Beams (FRIB), ILC ... large facilities
  - *NSAC report states that as a res... al advances, a ... rare isotope fa... can be built at ≈ half the ... riginally planned ... pe Accelerator (... employing a supe... g linac*
- SRF at 2K is ... operating at ... further redu... sts as the cryogenic cooling moves tow... shelf cryo-c...
- Replacing bulk Nb ... ated Cu caviti... also reduce costs
- The ultimat... would be fro... ust Al SRF cavities coated with higher temperature supercondu... , Mo_3Re, Nb_3Sn, MgB_2, oxypnictides)

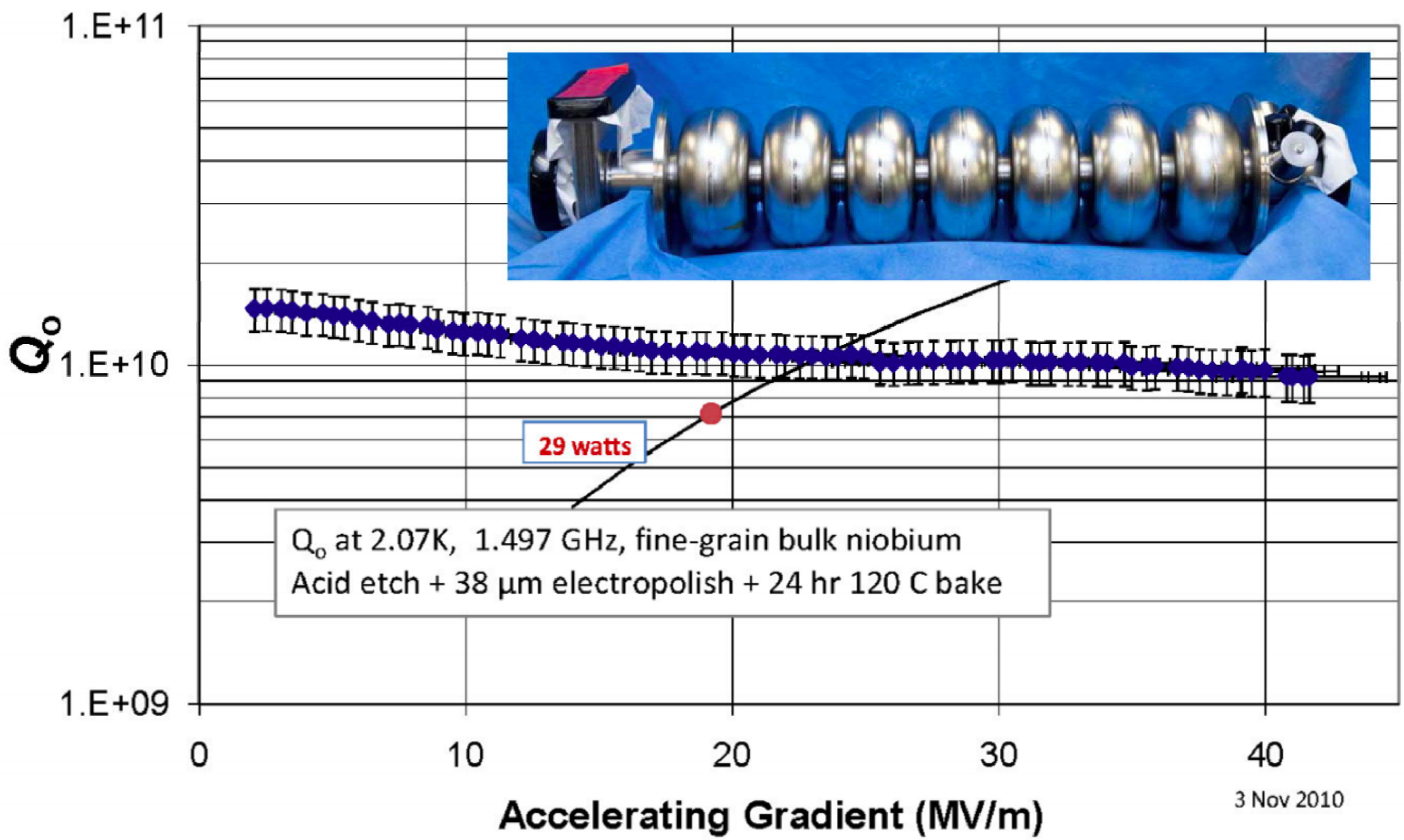
SRF uses less power than normal

SRF with cheaper cavity materials (Cu) would be better

SRF with cheaper cavity materials and high-T_c thinfilms would be better still

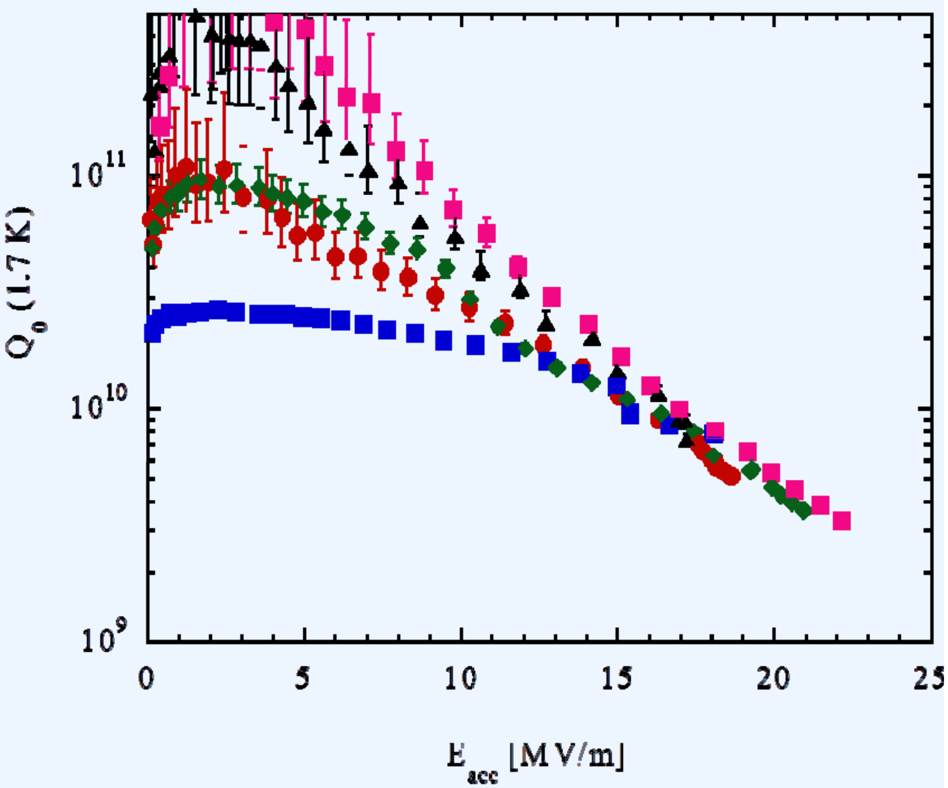
AASC's thin film superconductor development is aimed at these goals

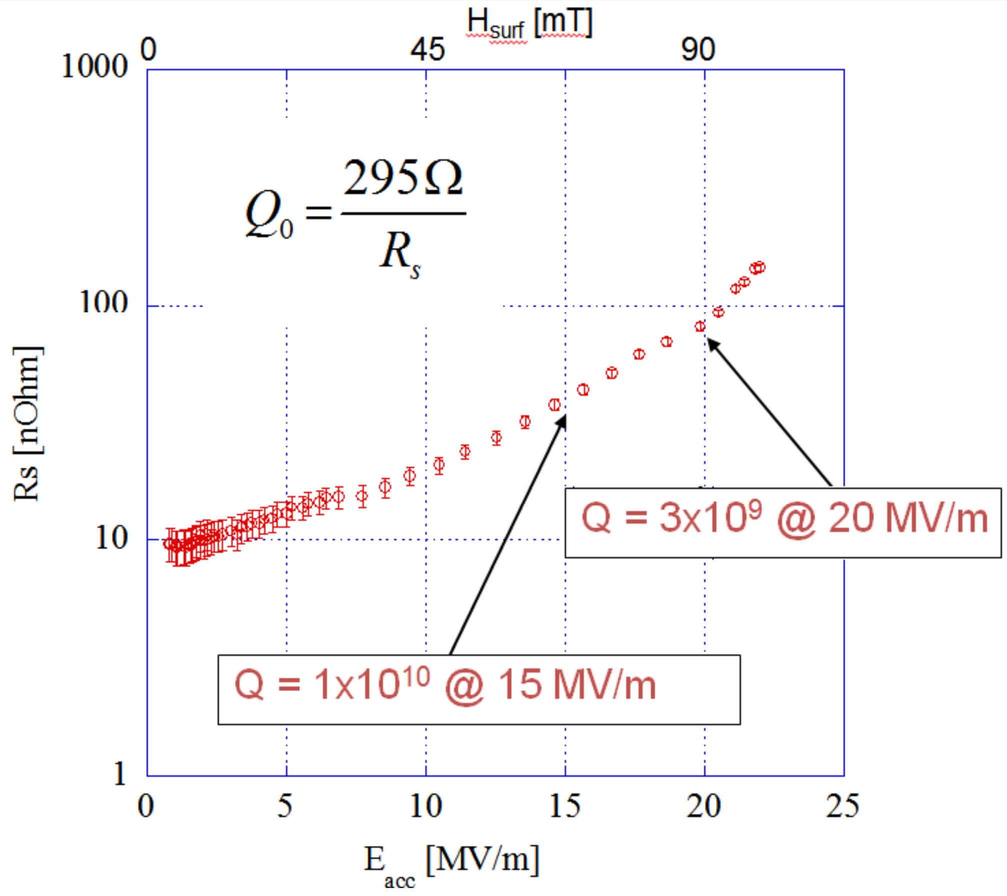
Ideal Nb Bulk Cavities



(*Q* is BCS-limited)

CERN results: Nb films sputtered onto copper cavities

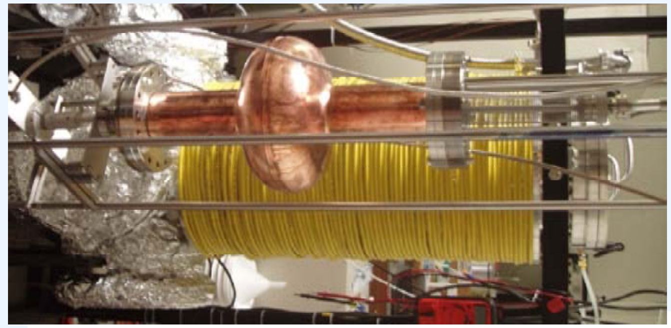


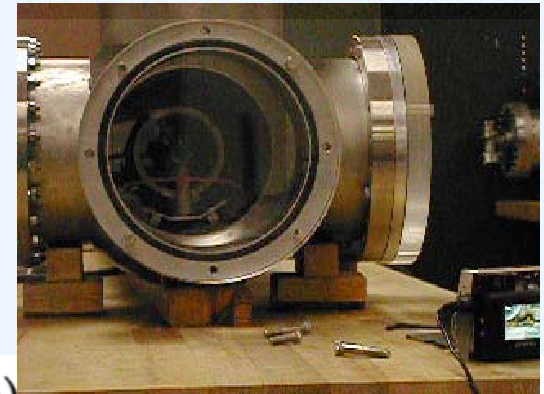


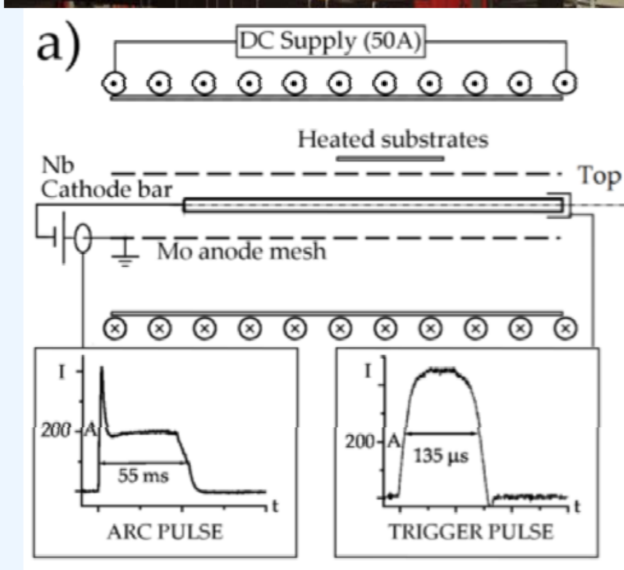
CERN magnetron sputtering

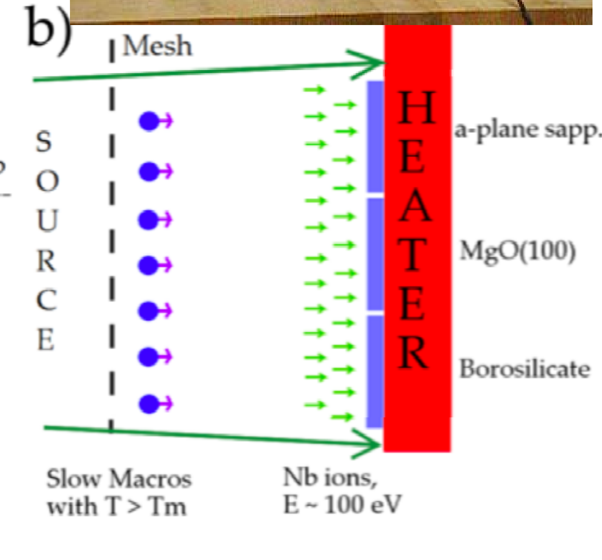
Coaxial Energetic Deposition (CED) Coater at AASC

Coaxial Energetic Deposition (CED™)









- CED coater uses "welding torch" technology
- Arc source is scalable to high throughputs for large scale cavity coatings
  - Present version deposits ≈1 monolayer/pulse in ≈1ms
- Russo's and Langner's emphasis on UHV and clean walls is important

CAD: Pulsed Biased deposition; Dual Targets

Cathodic Arc Deposition (CAD)

Pulsed Bias capability

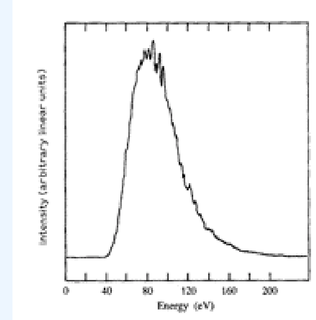
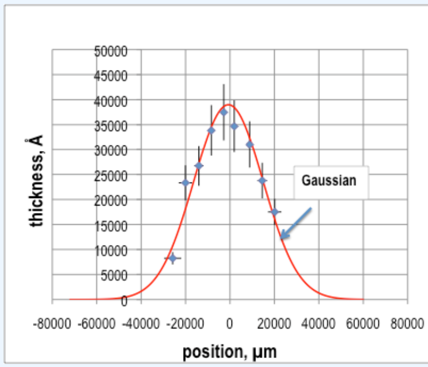
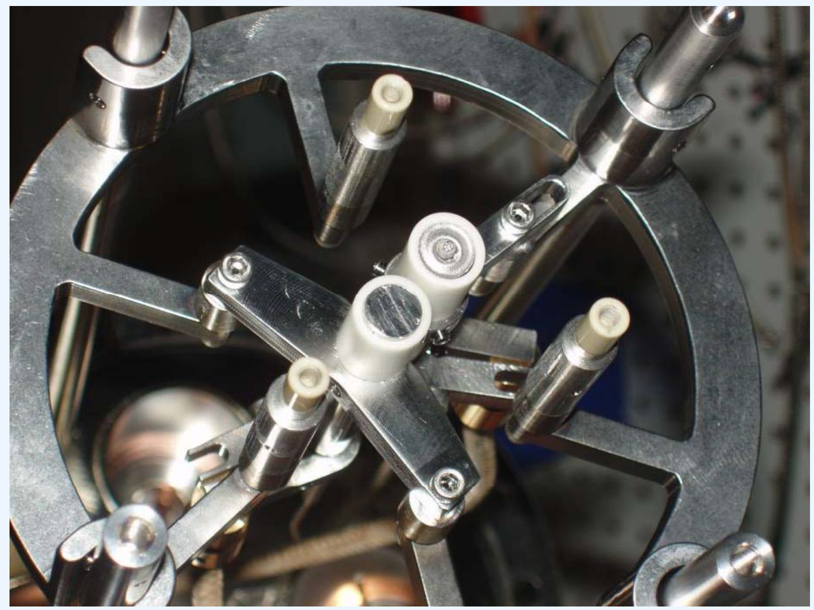


Figure 1 Energy distribution of Nb ions from a 95 A d.c. filtered arc.

* A. BENDAVID, P. J. MARTIN, R. P. NETTERFIELD, G. J. SLOGGETT, T. J. KINDER, C., ANDRIKIDIS, JOURNAL OF MATERIALS SCIENCE LETTERS 12 (1993) 322-323



vol under gaussian=	0.012	cc
mass under gaussian=	0.100	g
mass/shot=	14.3	µg
charge/shot=	0.5	C
anode transm.=	0.7	
erosion rate=	41	µg/C
peak thickness/pulse=	5.6	Å
instant. rate=	5600	Å/s



Dual Target source for Nb_3Sn, Mo_3Re, MgB_2 etc.

Challenges for thin film SRF: path to success

- Cu and/or Al cavity substrates might be of two different forms

- How do we grow low-defect Nb films on such substrates?
- Study adhesion, thickness, smoothness, RRR, stability
- Understand these issues at the coupon level
- Proceed to RF cavity level and measure Q at high fields
- Install multi-cell Nb coated Cu modules in SRF accelerator and validate the thin film solution
  - Spur acceptance of thin film Nb by accelerator community
- Continue R&D towards higher T_c films and Al cavities

Publications over the past year-I

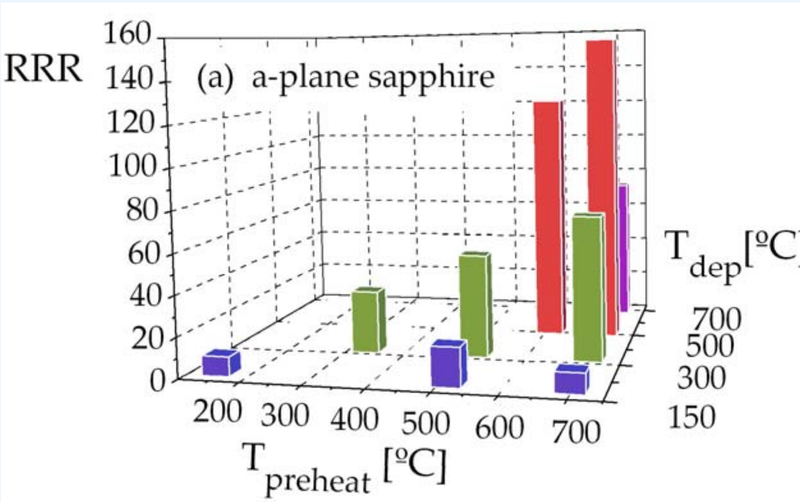
1. M. Krishnan et al, “Energetic Condensation Growth of Nb films for SRF Accelerators”, Thin Films and New Ideas for Pushing the Limits of RF Superconductivity, SRF Workshop Proceedings, Padua, Italy, **October 2010**.
2. E. Valderrama et al, “High RRR Thin Films of Nb Produced using Energetic Condensation from a Coaxial, Rotating Vacuum Arc Plasma (CED^{TM})”, Cryogenic Engineering Conference & International Cryogenic Materials Conference, Washington, CEC-ICMC-11, USA, **June 2011**. (in press).
3. M. Krishnan et al, “Energetic Condensation of Nb thin films”, Proceedings of SRF-2011, USA, 2011. TUIOB01, **July 2011**.
4. E. Valderrama et al, “Nb film growth on crystalline and amorphous substrates”, Proceedings of SRF-2011, USA, 2011. THPO069, **July 2011**.
5. E. Valderrama et al, "Mo-Re films for SRF applications", Proceedings of SRF-2011, USA, 2011. THPO077, **July 2011.**

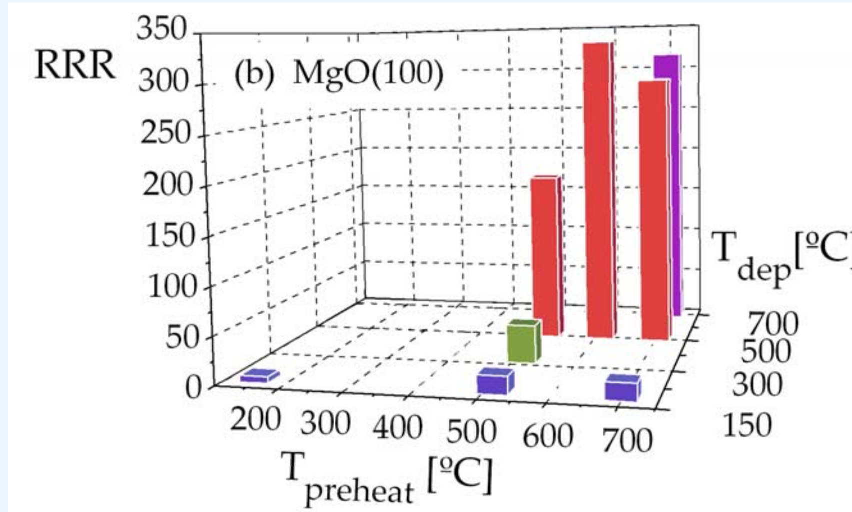
Publications over the past year-II

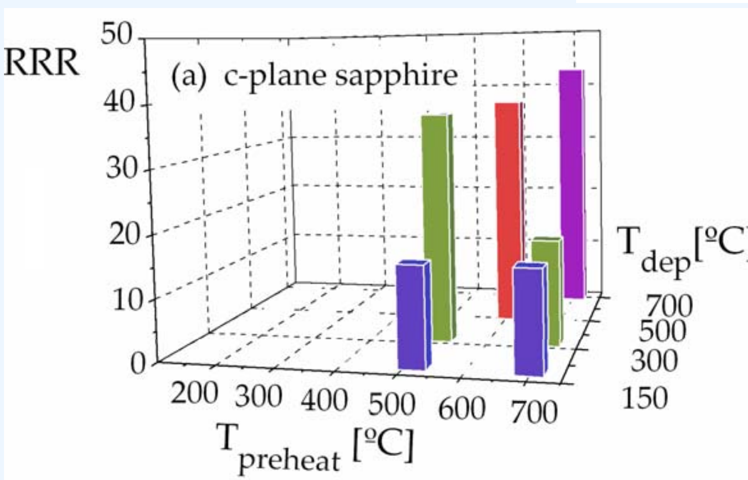
6. K. Seo et al, "Crystallographic Orientation of Epitaxial Transition Observed for Nb (bcc) on MgO and Cu (fcc) Single-crystals", Proceedings of SRF-2011, USA, 2011, THPO042, **July 2011**.
7. X. Zhao et al, "Twin symmetry texture of energetically condensed niobium thin films on sapphire substrate (a-plane Al_2O_3)," Journal of Applied Physics, vol. 110, p. 033523**, August 2011.**
8. T. Tajima et al, "Bulk-like Nb Films might be Possible with Coaxial Energetic Deposition for Superconducting RF Cavities", AVS Meeting, **October, 2011**.
9. M. Krishnan et al, "Very high residual-resistivity ratios of heteroepitaxial superconducting niobium films on MgO substrates," Superconductor Science and Technology , vol. 24, p. 115002, **November 2011**.

AASC's CED coated Nb films match RRR of bulk Nb!

- Nb thin films grown on sapphire and MgO crystals have demonstrated higher levels of RRR than were reported by the pioneers, and XRD spectra reveal crucial features







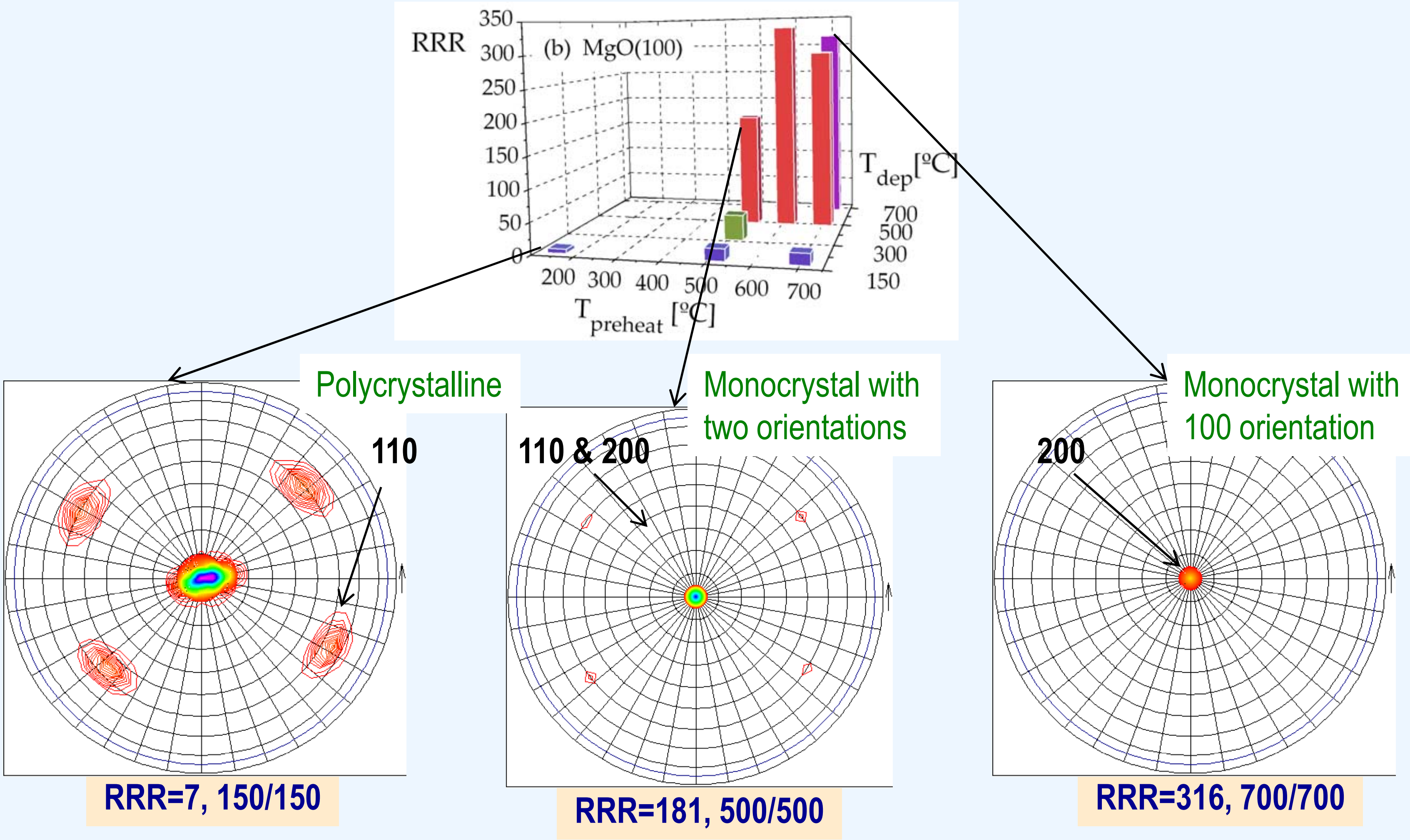
RRR-585 (±1% error) measured on 5µm film on

RRR-330 measured on a-sapphire

- M. Krishnan et al, "Very high residual-resistivity ratios of heteroepitaxial superconducting niobium films on MgO substrates," Superconductor Science and Technology , vol. 24, p. 115002, November 2011

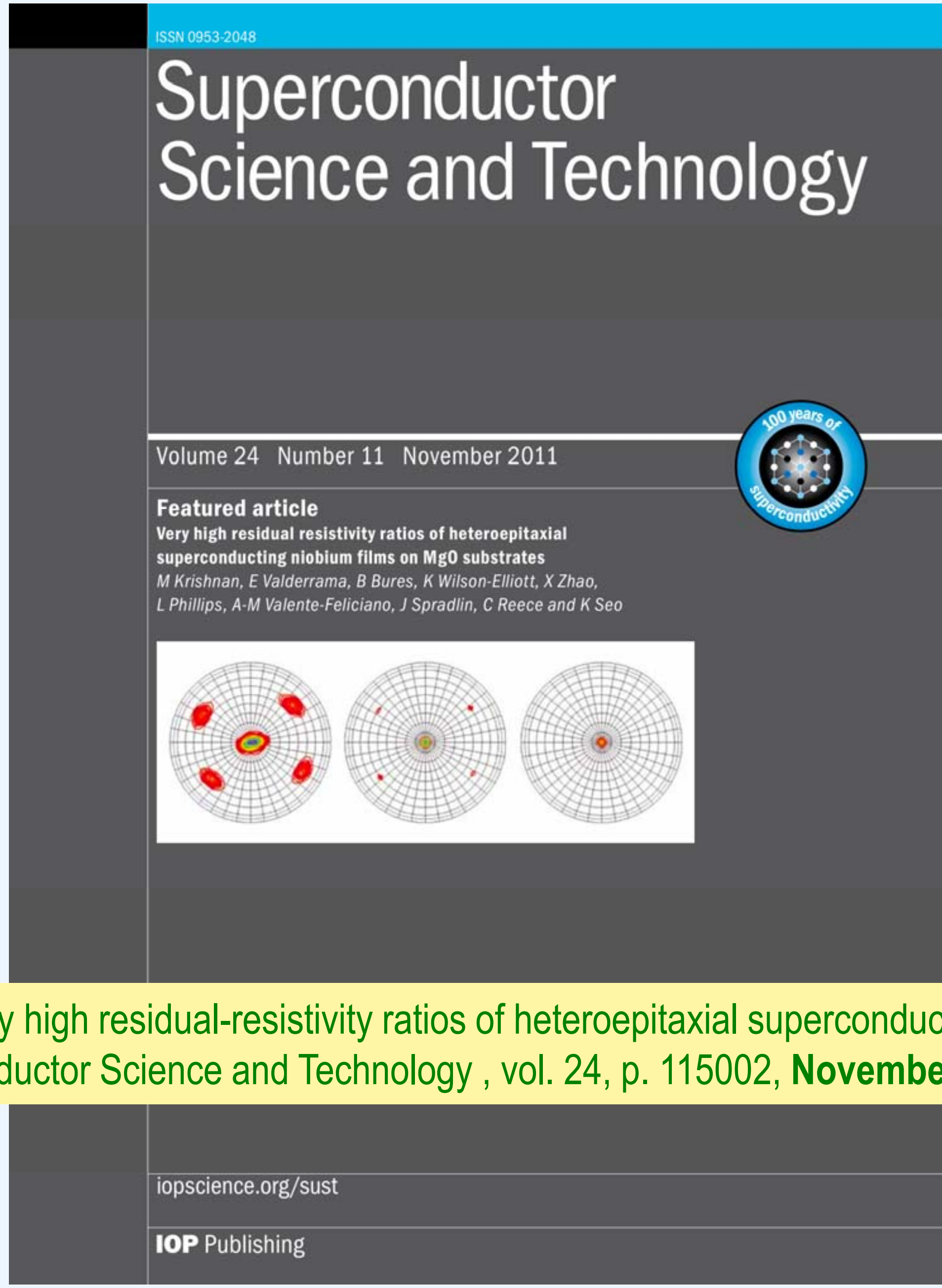
RRR of Nb thin films on MgO substrates

- Pole Figures show change in crystal orientation from 110 to 200 at higher temperature



- K. Seo et al, "Crystallographic Orientation of Epitaxial Transition Observed for Nb (bcc) on MgO and Cu (fcc) Single-crystals", Proceedings of SRF-2011, USA, 2011, THPO042, July 2011

One paper selected as Featured Article for SUST: Nov. 2011



M. Krishnan et al, "Very high residual-resistivity ratios of heteroepitaxial superconducting niobium films on MgO substrates," Superconductor Science and Technology , vol. 24, p. 115002, **November 2011**.

Observations about bulk single crystal Nb orientation

PERFORMANCE OF SINGLE CRYSTAL NIOBIUM CAVITIES, **P. Kneisel**, G. Ciovati, TJNAF, Newport News, VA 23606, U.S.A. W. Singer, X. Singer, D. Reschke, A. Brinkmann, Proceedings of EPAC08, Genoa, Italy MOPP136

PROGRESS ON LARGE GRAIN AND SINGLE GRAIN NIOBIUM – INGOTS AND SHEET AND REVIEW OF PROGRESS ON LARGE GRAIN AND SINGLE GRAIN NIOBIUM CAVITIES, **P. Kneisel**, Proceedings of SRF2007, Peking Univ., Beijing, China

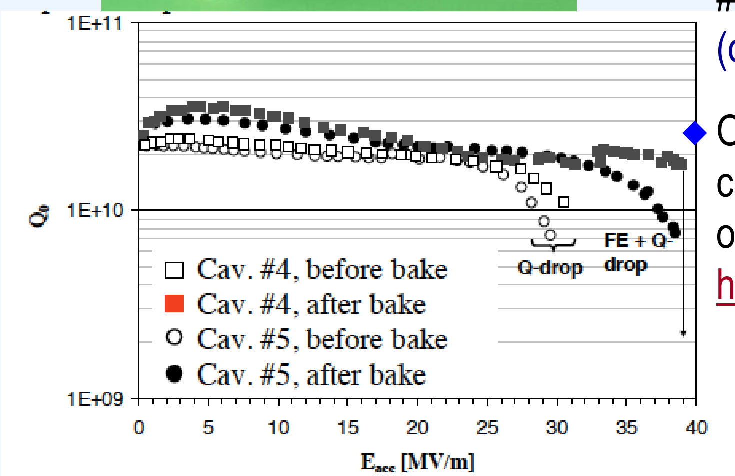
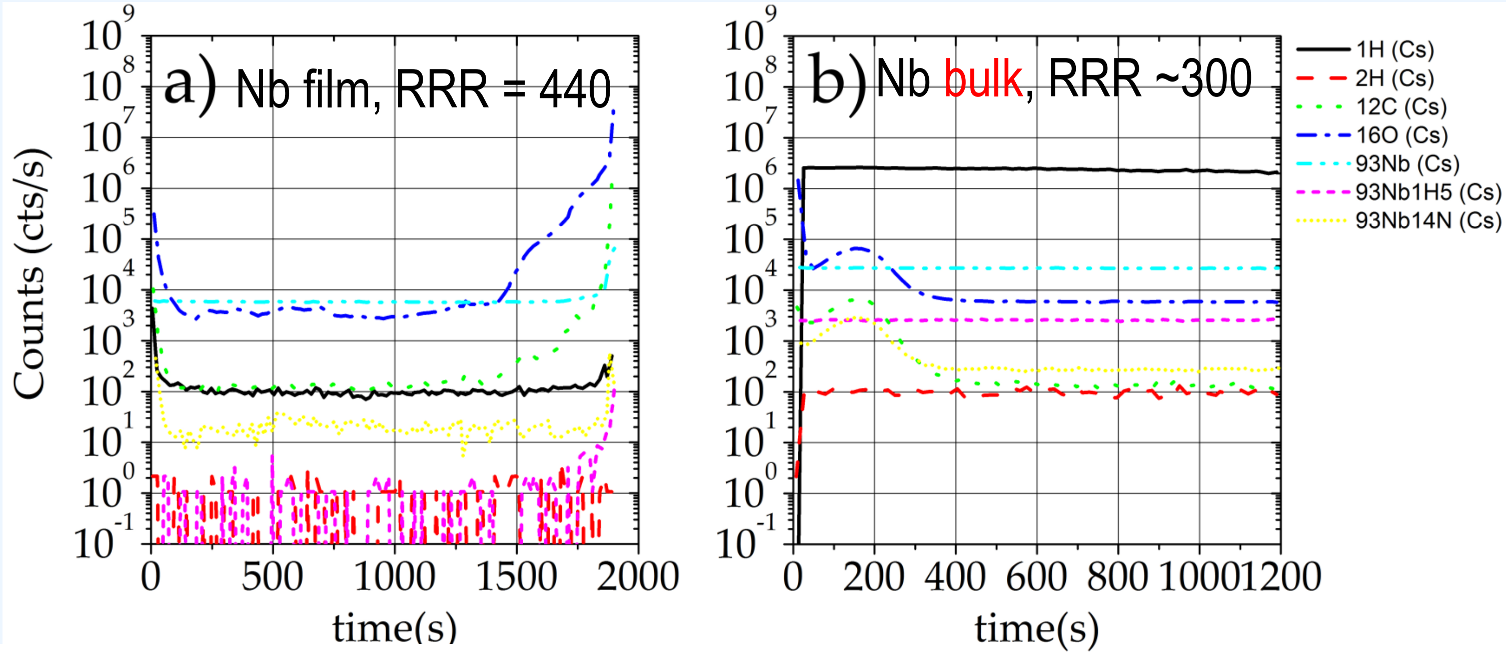


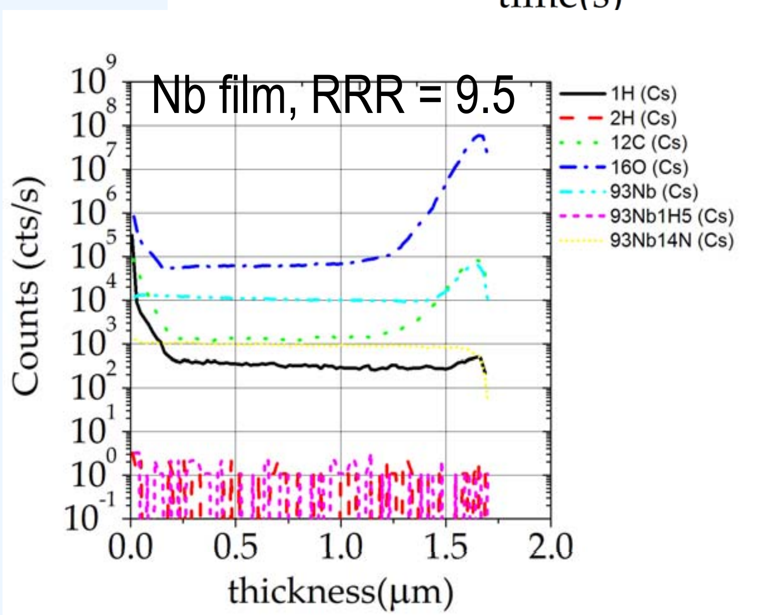
Figure 4: Q_0 vs. E_{acc} at 2 K for single crystal cavities #4 and #5 (best performance).

- Cavity #5 showed a different behavior than all other single crystal/large grain cavities after baking: the Q-drop did not disappear after 12 hours. The crystal orientation of the single crystals of this cavity was (110) with a tilt against the surface. For cavity #4 the crystal orientation was (100).
- The surface of both cavities appeared quite different after BCP: whereas cavity #4 exhibited a very smooth, shiny surface, the surface of cavity #5 was "rough" (orange peel/fish scale appearance) and less shiny.
- Obviously, there is a difference in the reaction of the BCP chemicals at different crystal orientations {D. Baars et al., "Crystal orientation effects during fabrication of single or multi-crystal Nb SRF cavities", SRF07, Beijing, Oct. 2007, TH102; http://www.pku.edu.cn/academic/srf2007/proceeding}

Could CED (Energetic Condensation) be used to grow (100) Nb films on existing Nb cavities to help improve performance?

SIMS analysis of CED films to study impurities





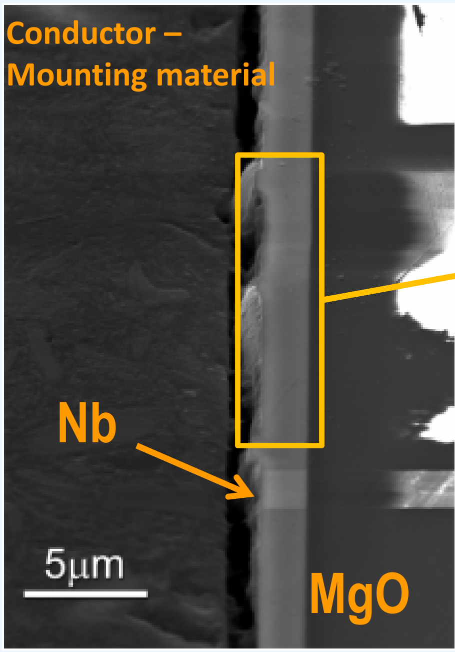
- The H count rate in CED film is 7000x lower than in bulk Nb!
- The Oxygen level in RRR=9.5 film is much higher
  - RRR=9.5 film was deposited at “room temperature”
- Role of NbO in flux pinning?

Summary and Future Plans

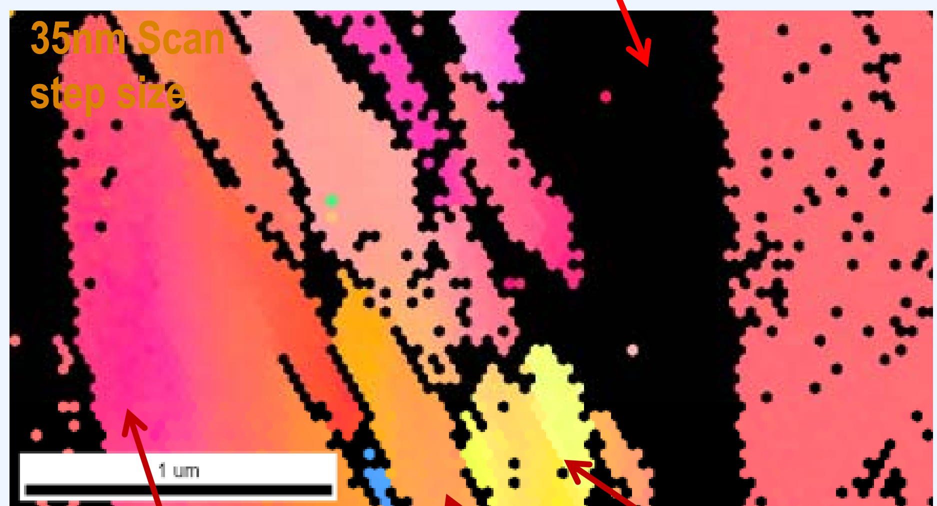
- Our RRR data show that our films match bulk Nb
- Our $B_{pen.}$ data also match bulk Nb
- Our densely packed films have 7000x less H than bulk Nb
- Next steps are to coat SRF cavities and test for Q-slope while continuing to improve high-T_c films such as Nb_3Sn and others
- Our CED energetic condensation process could have an impact on existing and future SRF designs
  - Nb-on-Cu bellows (APS) could be inserted into APS upgrades (G. Wu)
  - Nb-on-Nb cavitites could enhance existing SRF accelerators (P. Kneisel)
  - Nb-on-Cu cavities could have an impact on low-β SRF (FRIB et al)
  - NbN coatings could passivate Nb cells and improve reliability (G. Ciovati)
  - NbN coatings could (when integrated into multi-layer coatings a la Gurevich) boost maximum E-field in future designs
  - Nb_3Sn and MgB_2 coatings could increase T_c and reduce cost

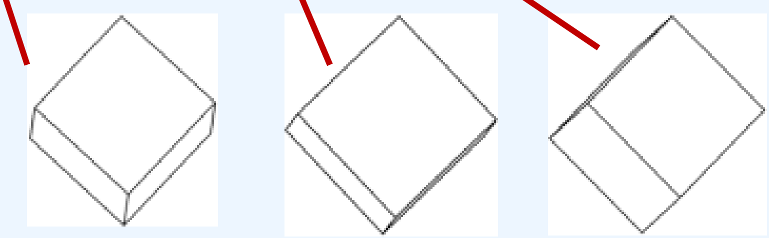
RRR–7: Cross sectional EBSD (OIM): textured crystal

BSE image – Cross sectional view



Lower CI values between Nb matrix and MgO substrate indicate that there could be an amorphous or non-structured layer between them

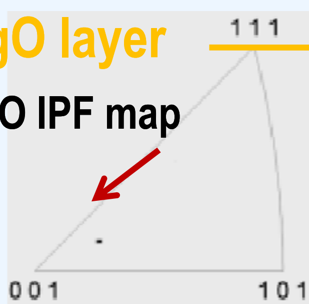




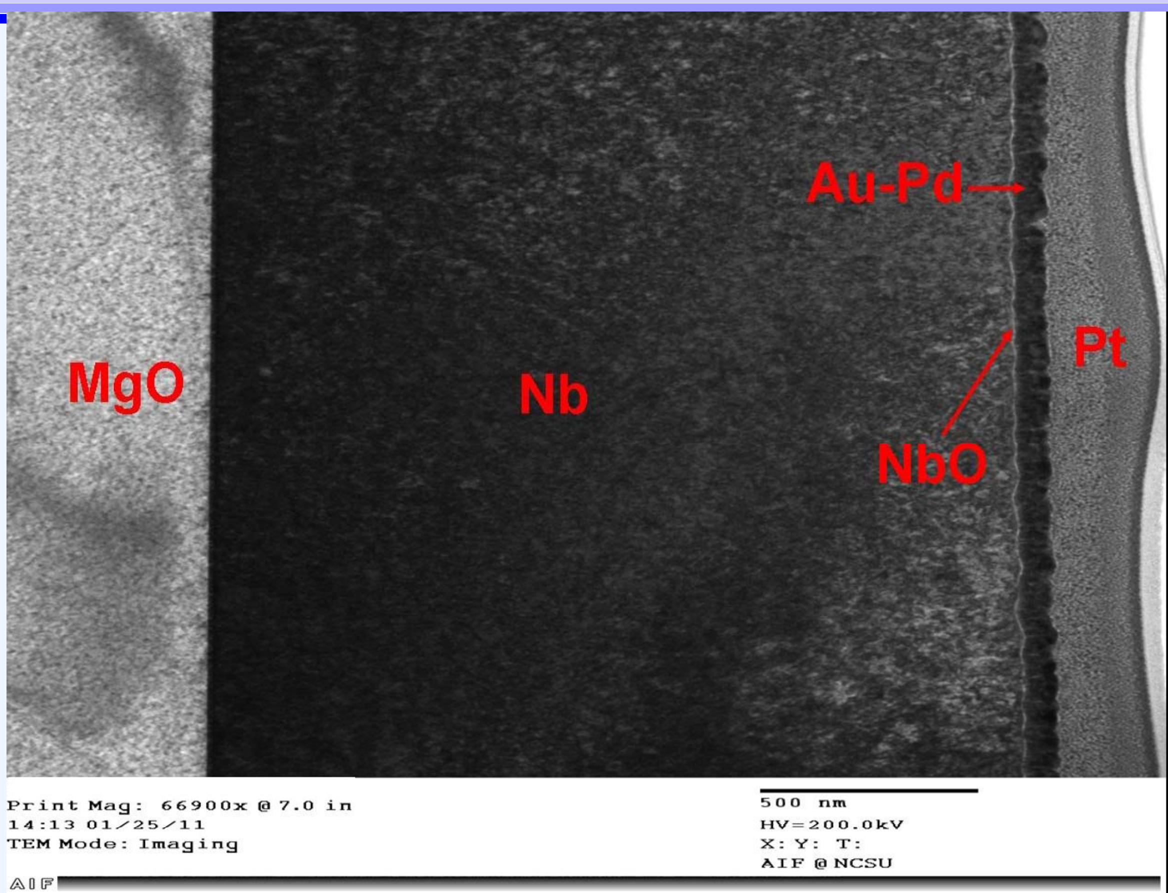
Nb thin film layer

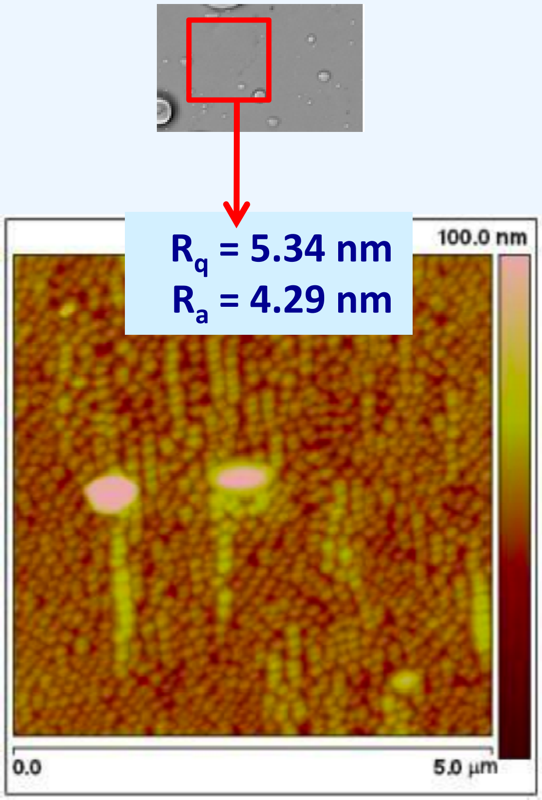
MgO layer

MgO IPF map



TEM/AFM of high RRR film: sharp interface with substrate





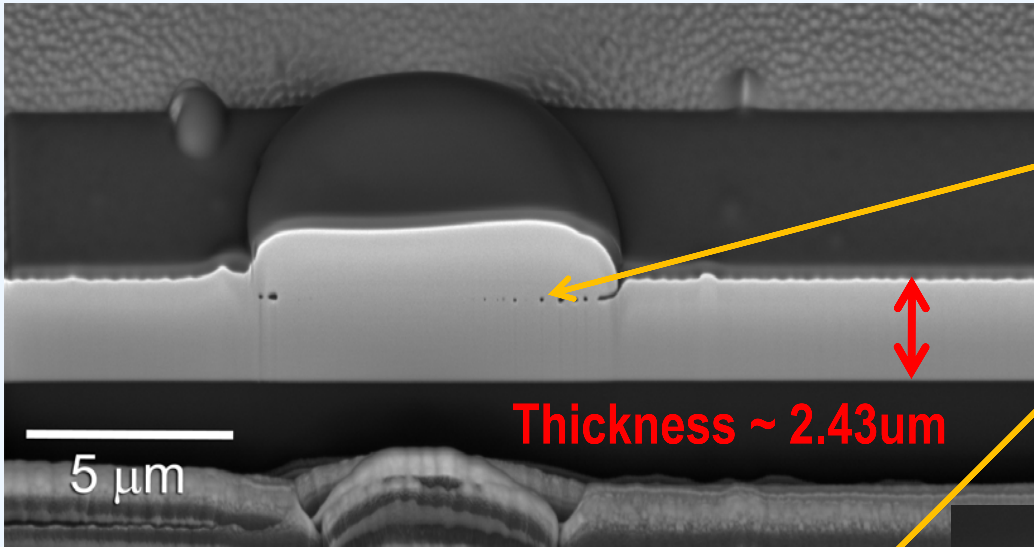
- ◆ Energetic Condensation (subplantation) physics drives an adhesive, non-porous, sharp interface between substrate and Nb film
- ◆ Nb surface is smooth (~5nm roughness)

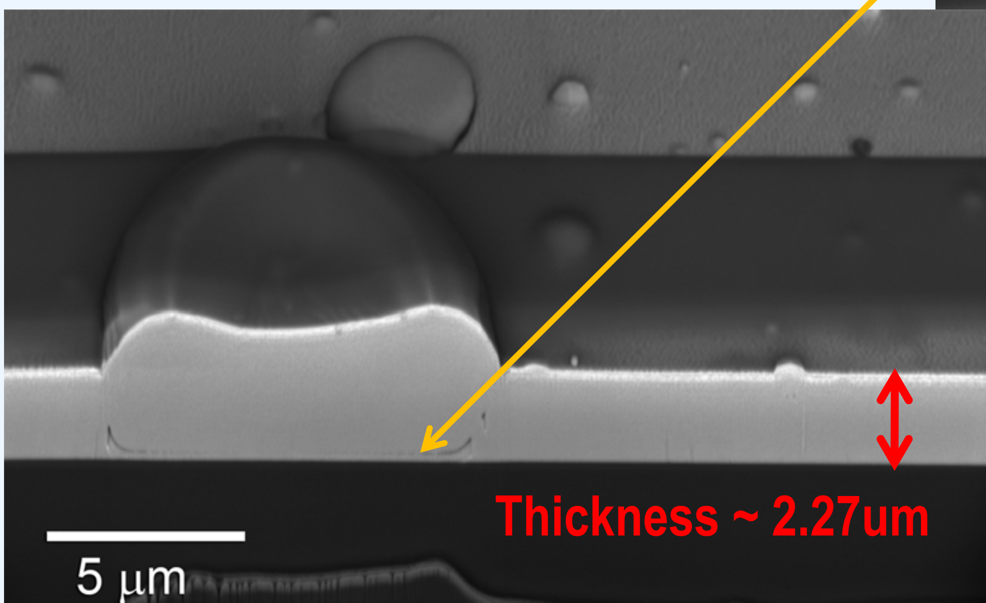
"Mold" effect of subplanted Nb films: high RRR film

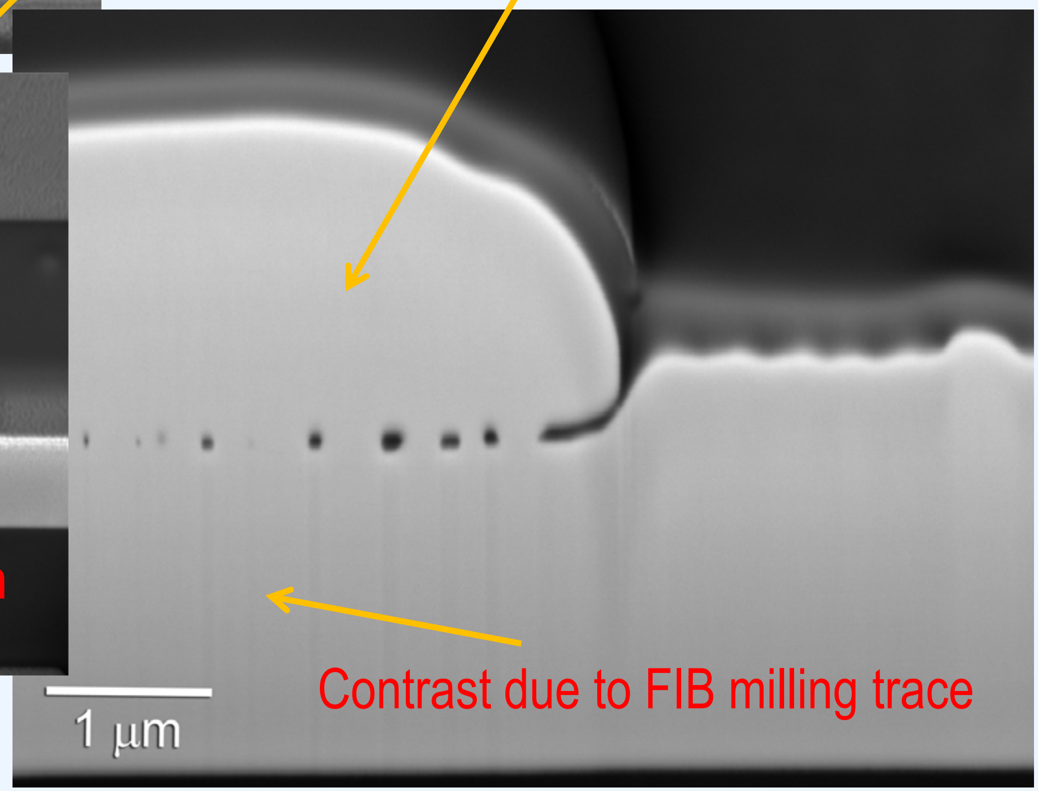
This macro landed on 2.4μm Nb film

This macro landed *near* MgO surface

No Columnar structure; XRD shows (100) single crystal

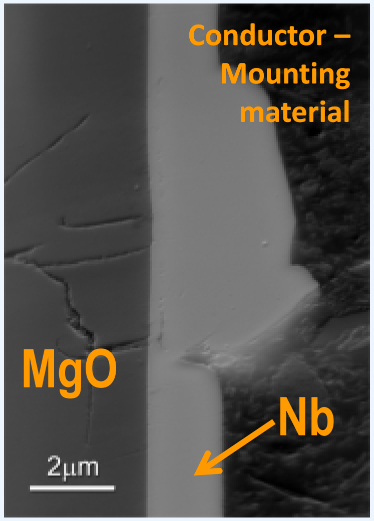


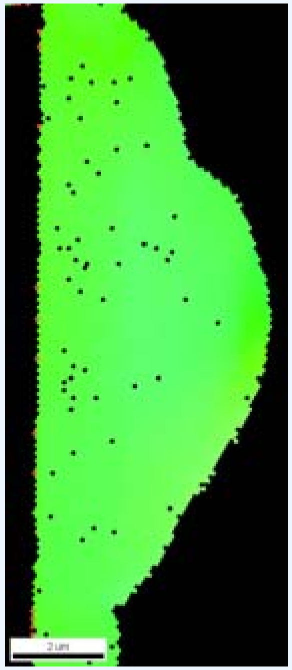


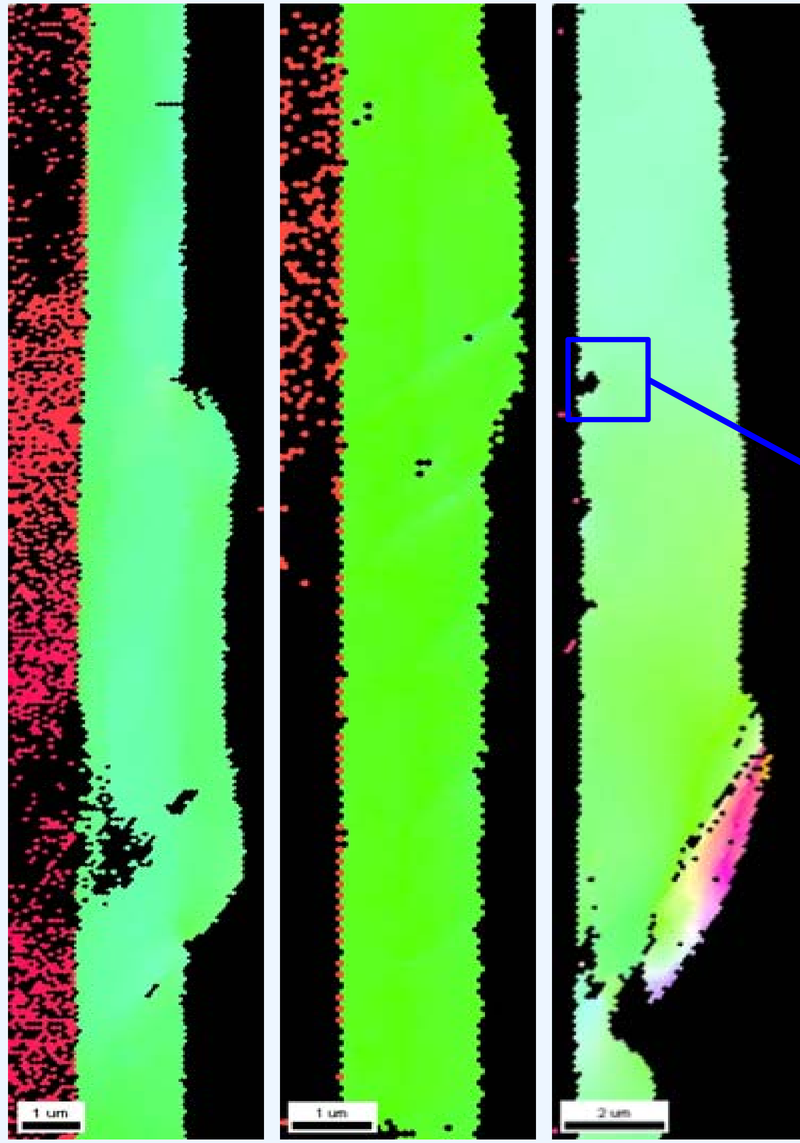


Contrast due to FIB milling trace

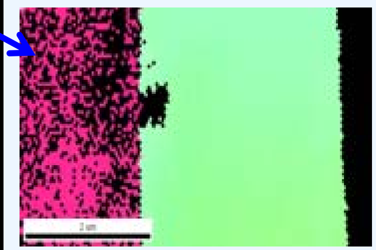
RRR–316: Cross sectional EBSD: dense, monocrystal film

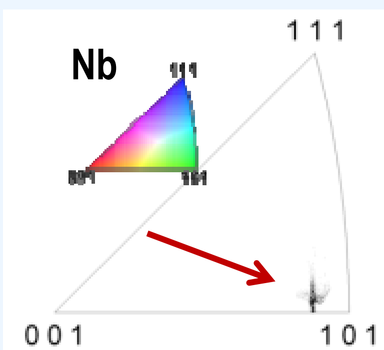


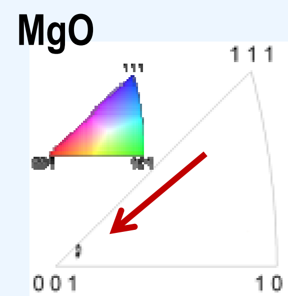




0.15µm scan step size



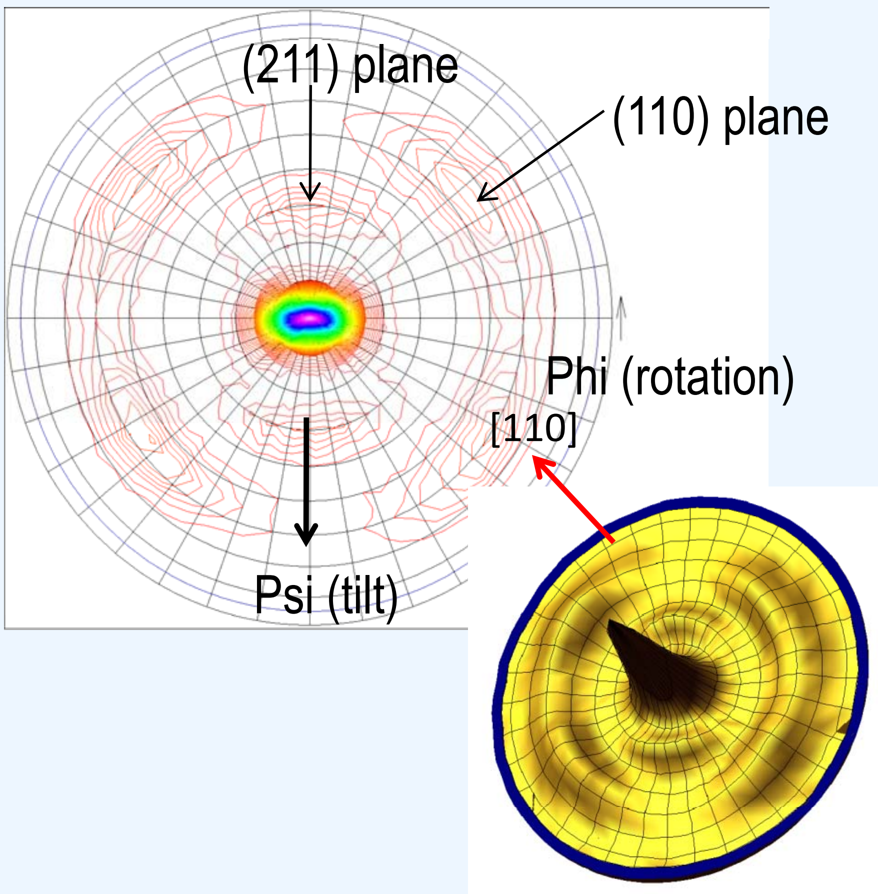




XRD Pole Figures for Nb thin films grown on Borosilicate

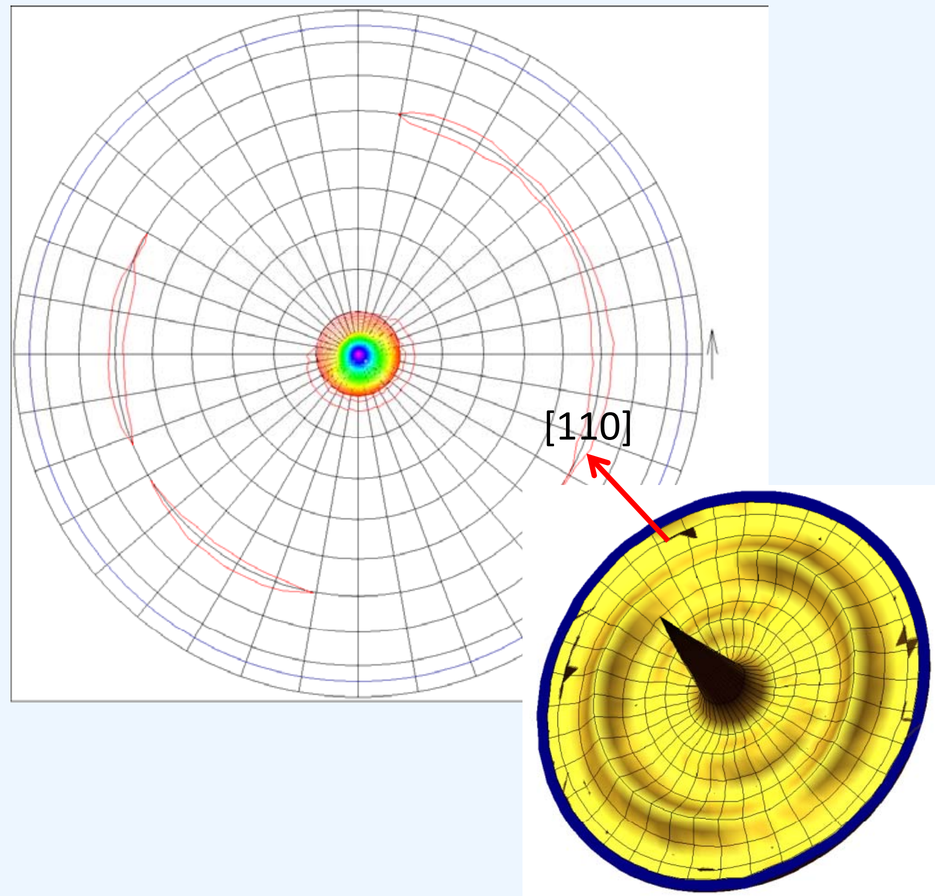
Subplantation physics of energetic condensation at work here

(110) Nb on Borosilicate at 150/150C



A strong [110] Nb fiber structure perpendicular to the substrate

(110) Nb on Borosilicate at 400/400C



At higher coating temperature, in-plane texture shows that [110] fiber texture is highly oriented to the substrate