Exploiting Recent Advances in Cavity Surface and Materials Research Toward a 1 TeV ILC Upgrade

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ALCPG11 – Linear Collider Workshop of the Americas, March 20, 2011

Acknowledgments:

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T. Prolier, C. Reece, A. Romanenko, A. Rowe, J. Zasadzinski

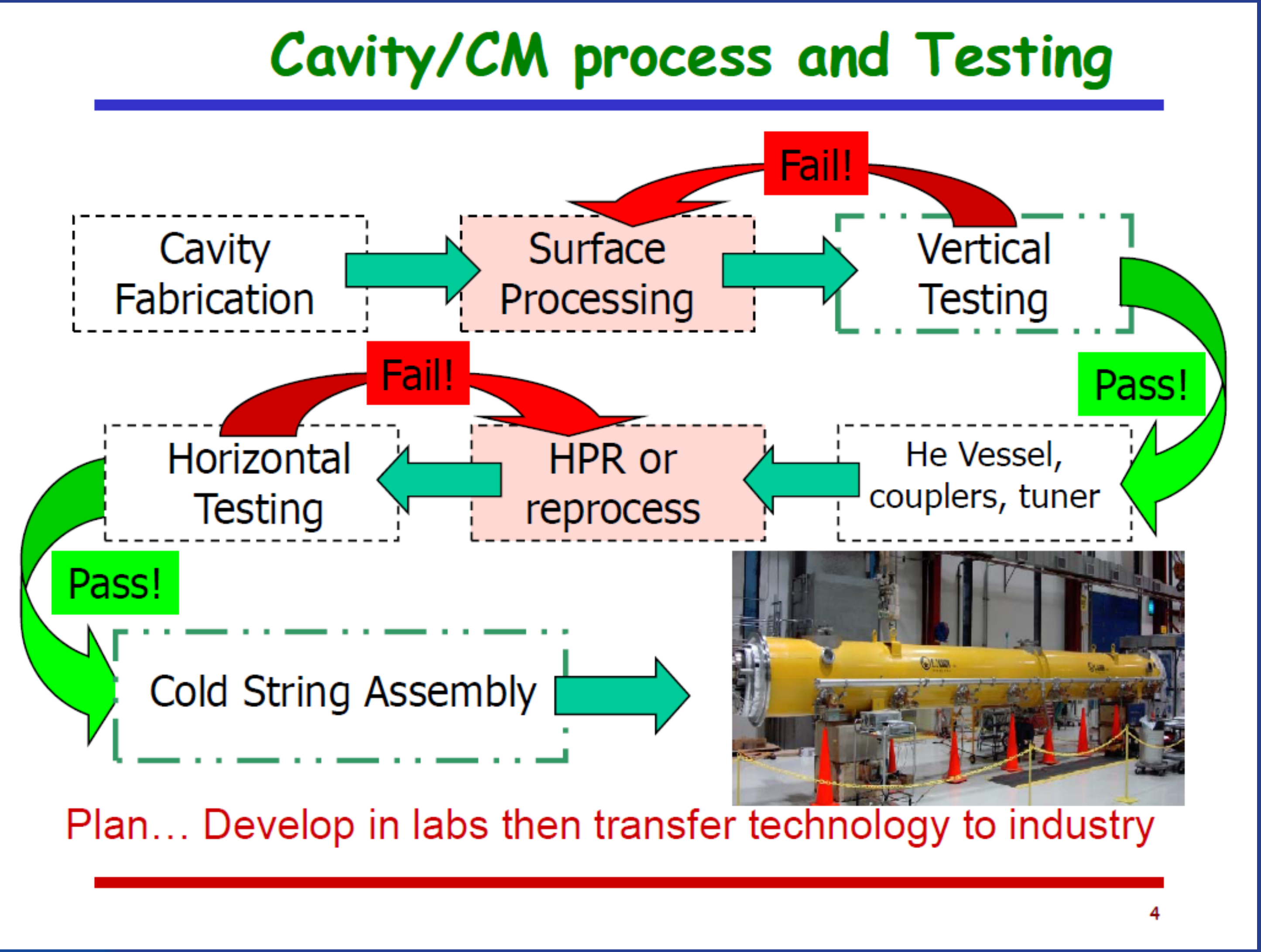
Charge and Context

- Consider long-term (10 year) SCRF cavity R&D toward a Main Linac upgrade to 1 TeV
  - What approaches are technically possible?
  - Looking forward, what long-term efforts should be integrated with the present R&D effort?

- Improvement by factors of 2 or even 10
  - Higher gradient and higher Q
  - Simplify, reduce cost, increase yield
  - Reduce hazards, lessen environmental impact

The present ILC industrialization plan

R. Kephart, 2010 SCRF Cavity Technol. & Industrialization Wkshp. / Kyoto



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The present ILC processing baseline

J. Kerby for the S0 Team, 2010 SCRF Cavity Technol. & Industrialization Wkshp. / Kyoto

	Standard Cavity Recipe
Fabrication	Nb-sheet (Fine Grain)
	Component preparation
	Cavity assembly w/ EBW
Process	BCP + 1st (Bulk) Electro-polishing (>120um)
	Ultrasonic degreasing with detergent, or ethanol rinse
	High-pressure pure-water rinsing
	Hydrogen degassing at > 600 C
	Field flatness tuning
	2nd Electro-polishing (~20um)
	Ultrasonic degreasing or ethanol rinse
	High-pressure pure-water rinsing
	Antenna Assembly
	Baking at 120 C
Vertical Test	Performance Test with temperature and mode measurement →inspection, reprocessing, other remediation

Industry

Inspection & remediation

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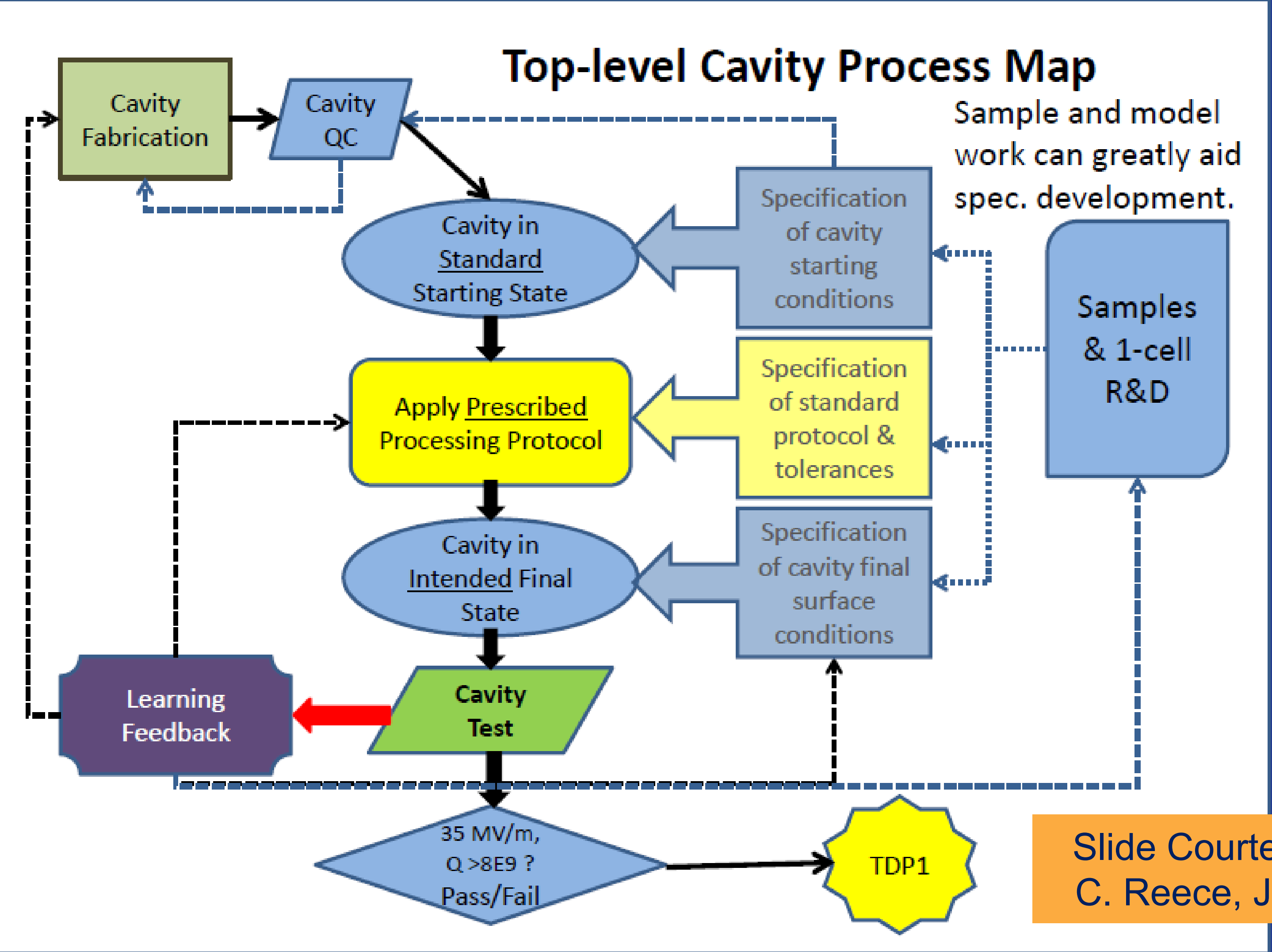
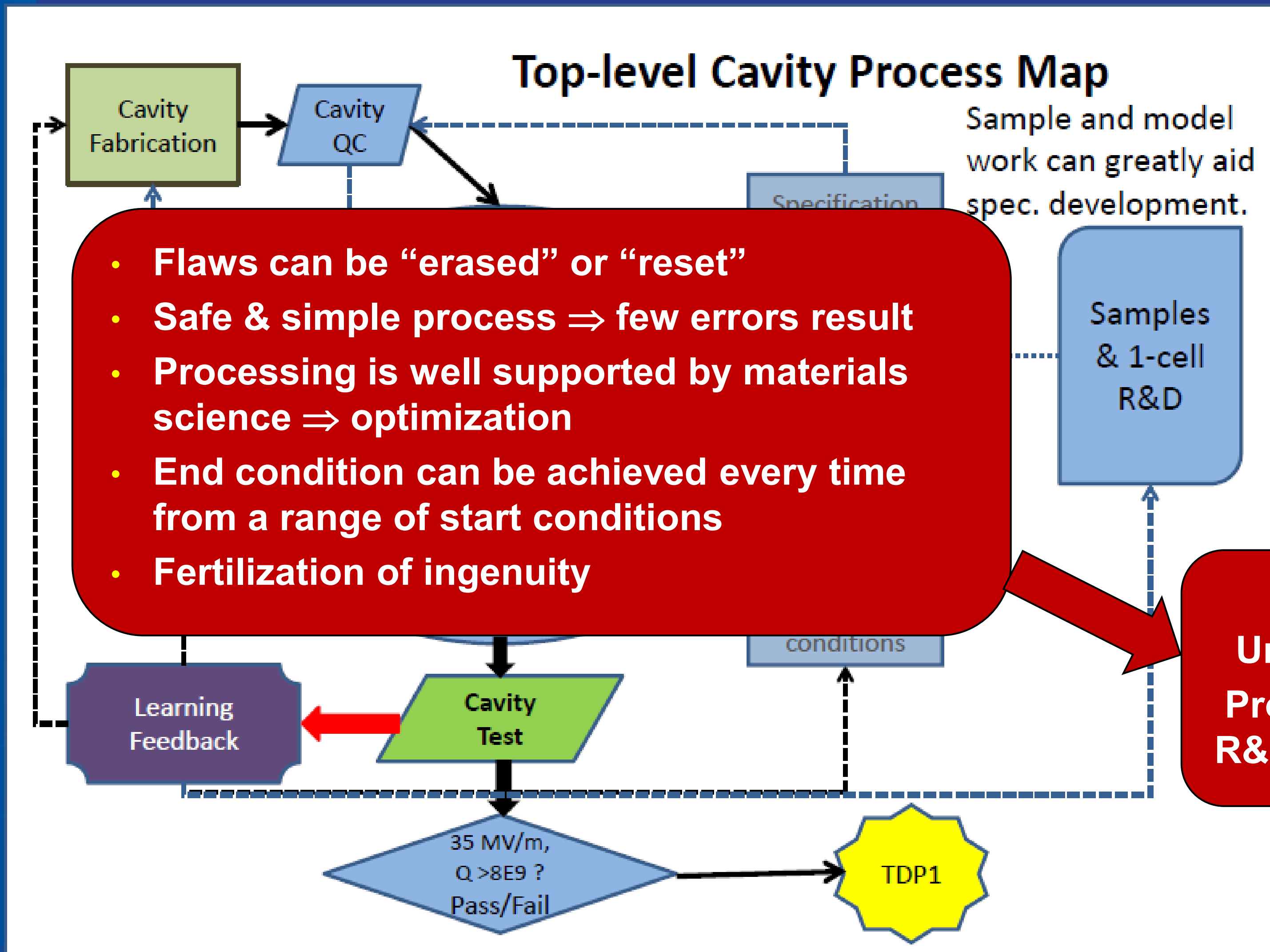
Pathway #1: Proscriptive extensions of the present baseline (next presentations)



Slide Courtesy of C. Reece, J-Lab

Pathway #2: Alternate processes that are more forgiving, adaptable, simpler, cheaper



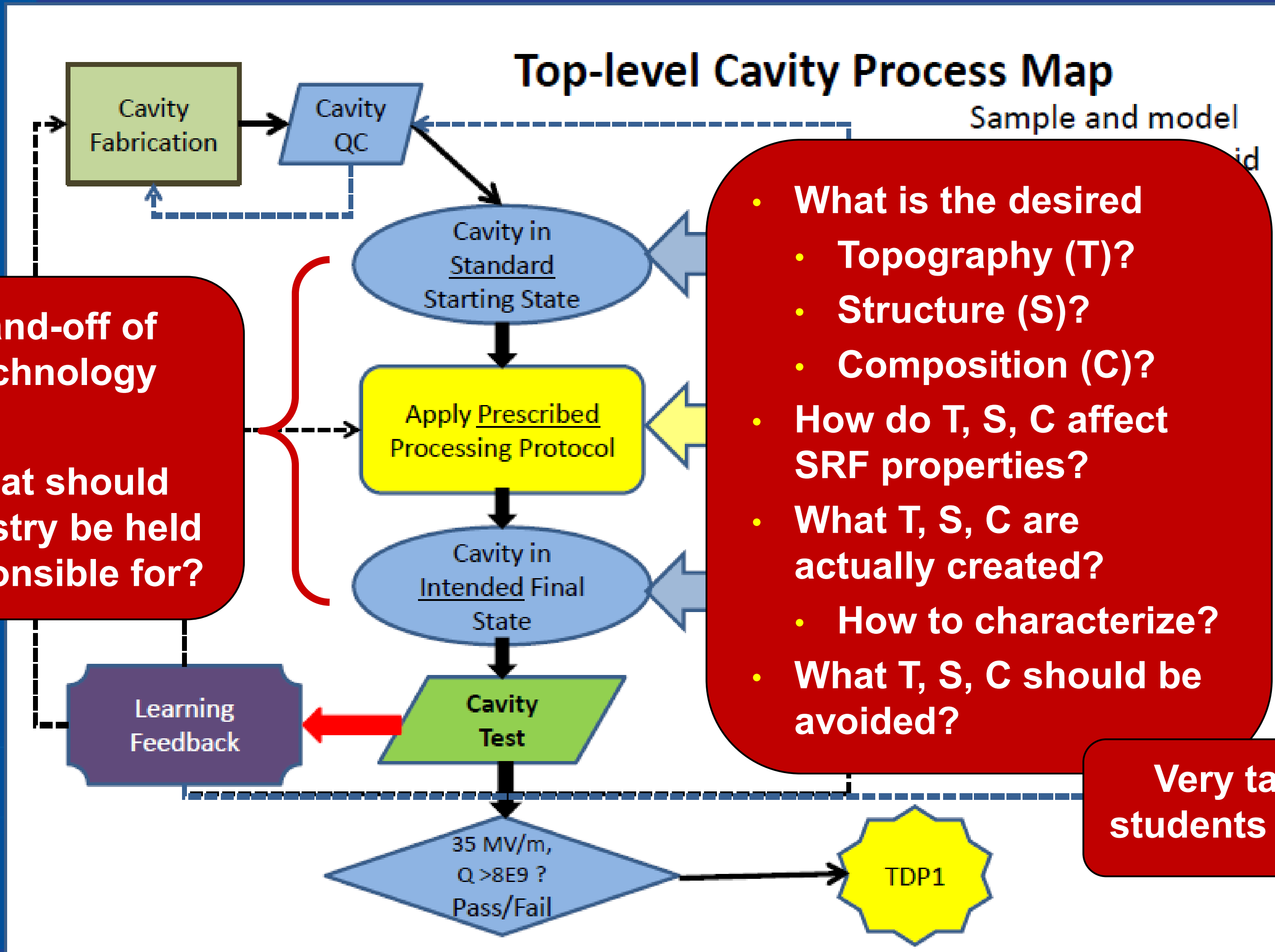
- Flaws can be "erased" or "reset"
- Safe & simple process ⇒ few errors result
- Processing is well supported by materials science ⇒ optimization
- End condition can be achieved every time from a range of start conditions
- Fertilization of ingenuity

SBIRs
Univ. R&D
Processing R&D at Labs

Promising Alternate Processes

- Cavity Hydroforming and Nb Tube R&D
  - Must support both areas in a coordinated program
- Extended CBP / tumbling / mechanical polishing
  - Transformational — Very smooth surfaces, forgives / repairs flaws, low-tech, eco-friendly
  - Can the process be completely free from toxic acids?
  - Adapt polishing to other cavity shapes?
- Alternatives to HPR
  - E.g. Peel-off coatings used to clean telescope mirrors
- High-power deposition of films
  - Recent breakthroughs bring RRR up above 300
- End group manufacturing
  - Can this be done as a solid piece? With simple welds?

Guidance comes from physics and materials science



Hand-off of technology

What should industry be held responsible for?

- **What is the desired**
  - **Topography (T)?**
  - **Structure (S)?**
  - **Composition (C)?**
- **How do T, S, C affect SRF properties?**
- **What T, S, C are actually created?**
  - **How to characterize?**
- **What T, S, C should be avoided?**

Very talented students & Ph.D.s

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R&D opportunities motivated by physics & materials science

- Dry cleaning techniques, e.g. plasma cleaning
  - Apply just after 800 °C bake
  - Integrate cleaning station with regular processing
- Protective coatings & Hydrogen barriers
  - Develop an atomic layer deposition process that integrates with regular cavity processing
- Not discussed here: multilayers, other materials
  - These may naturally evolve from films and coatings
  - Long pathway toward an engineering form

Characterization R&D

- Wider use of grain orientation imaging
  - How does texture affect processing?
    - Proscribed textures
    - Textures tolerant of processing variations
- Methods to map field emitter locations
  - Are emitters always the result of a process flaw, or are some due to materials?
  - Grand challenge – Only nacent R&D ideas at present!
- Coupon Cavities
  - Permits rapid processing feedback

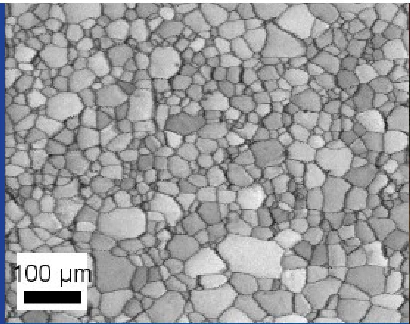
PROMISING ALTERNATE PROCESSING ROUTES

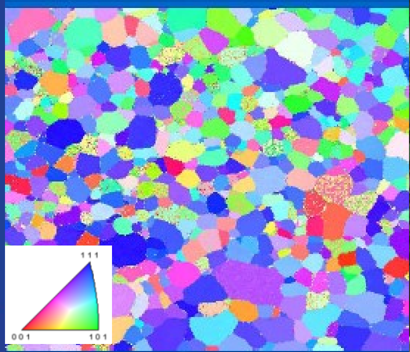
Hydroforming

- DESY has proven the principle with 3x3 cavities
  - Several review presentations by Waldemar Singer
- Extensive exploration by J-Lab & KEK, too
- Tube technology has emerged, is now ready
  - ATI Wah Chang now sells 150 mm x 1.5 m x 4 mm wall fine-grained seamless tubes (see next slide)
    - Billet process integrated with extrusion & forming
- FNAL has an active RFP with ILC-ART funding
  - Motivation: Reduce welds and weld defects
  - Goal: complete 9-cell hydroformed cavities
    - Workshop on 1 Sept. 2010, several vendors interested
  - 9-cell cavities hoped for by September, 2012
  - Need end group R&D

Successful DOE-SBIR with follow-on:
Black Labs / Dynamic Flow Forming / ATI Wah Chang / J-Lab / FNAL

13 µm grains
Random orientation





R. Crooks et al.

Billet forging + back extrude + flow form

6" I.D. RRR Tubes at ATI Wah Chang

As flow-formed

For DESY Hydroforming Machine Size

1.65 m length
~ 3 mm wall

9

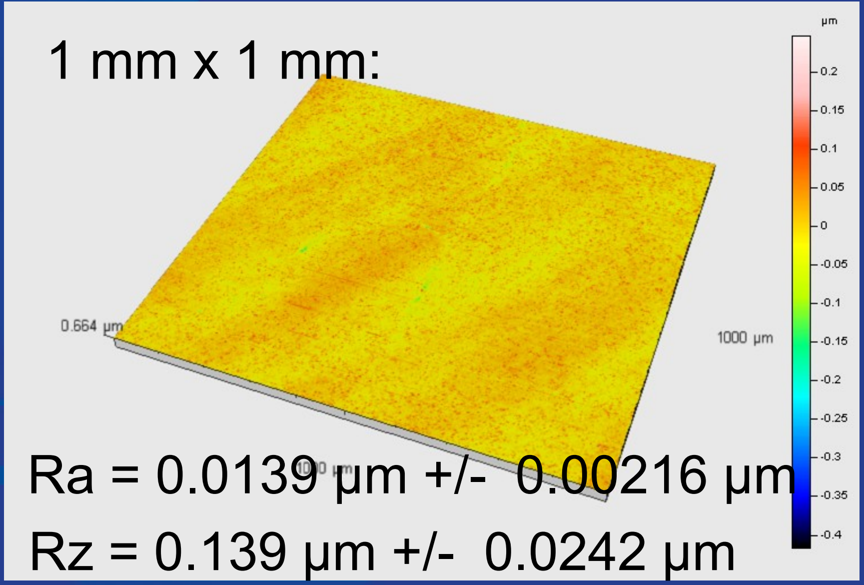
DOE SBIR DE-FG02-04ER83909

Niobium tube R&D

- Labs have ability to image grain orientations now
  - Very powerful at debugging raw material (e.g. tubes)
  - R&D: do grain orientations affect downstream processing?
- Reprocessing ideas
  - Texas A&M / Shear Form: Grain refinement, texture control, and weld healing by equal channel angular processing (SBIR)
    - Does not reduce diameter of tube while refining grains
    - Can cheaper tubes with inferior microstructures be tailored for hydroforming?
  - Nev.-Reno / Mich. State / Wah Chang: Zone induction annealing
    - Can reactor grade tubes be refined to RRR grade?
    - Single crystal tubes have been demonstrated
- Long term: are re-entrant hydroformed cavities possible?

Tumbling / Extended CBP

- Order-of-magnitude improvement in surface finish over EP
  - By a tech in a lab coat & safety glasses working in typical lab space.
- Thanks to pioneering work by Higuchi, Saito, Singer, others – Many groups already have a machine !
  - Assuredly, many exciting innovations are still to come



Courtesy C. Cooper, TTC Milan slides

Extending CBP* to fine polishing

Step 1

Cutting

+ Soap & Water

Step 2

Intermediate Polishing

+ Soap & Water

CBP

Step 3

Intermediate Polishing

400 grit Alumina + Water (~20 μm)

Step 4

Intermediate Polishing

800 grit Alumina + Water (~10 μm)

Step 5

Final Polishing

Colloidal Silica (0.05 μm)

Cooper's key observation: must soak the hardwood blocks in the slurry†

*Higuchi T et al., 1995 Proc. 7th Wkshp RF Supercond. (Saclay, Gif sur Yvette, France) p. 723.

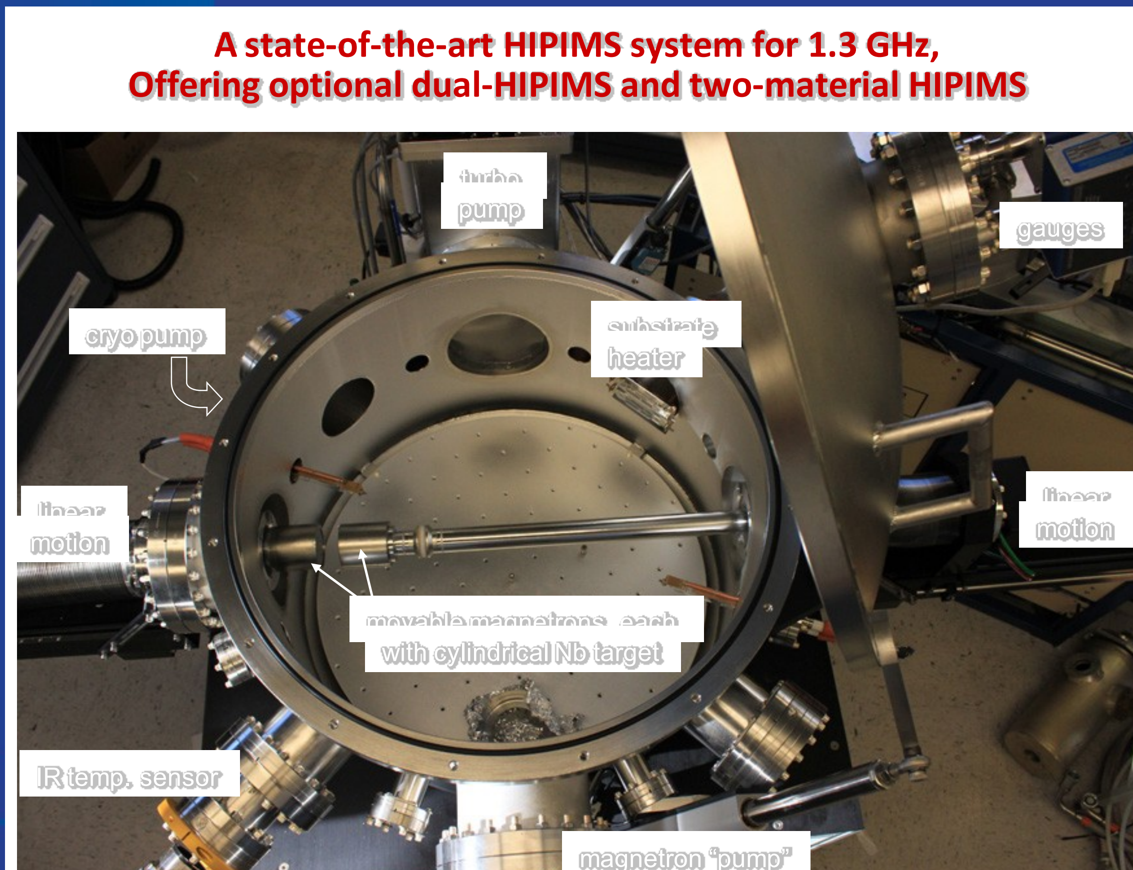
†Cooper C and Cooley L, Superconductor Science and Technology, submitted

Comments on tumbling

- Mirror smooth after step 5, best Q(E) after step 4 with final EP (so far – see Cooper's TTC slides)
  - Smearing traps media at ~10 μm scale when stage 5 is not applied long enough, just like coupon metallography
- More hydrogen – longer bake at 800 °C needed
  - Bake to p(H_2) and p(H_2O) standards?
- Parallel and scalable, few control "knobs"
- Can toxic acid be avoided completely?
- Does tumbling encourage re-entrant cavity R&D?

- Long term: Does step 5 enable an entirely new cavity paradigm where the RF surfaces are constructed from films and coatings on cheap Cu?

High power impulse magnetron sputtering

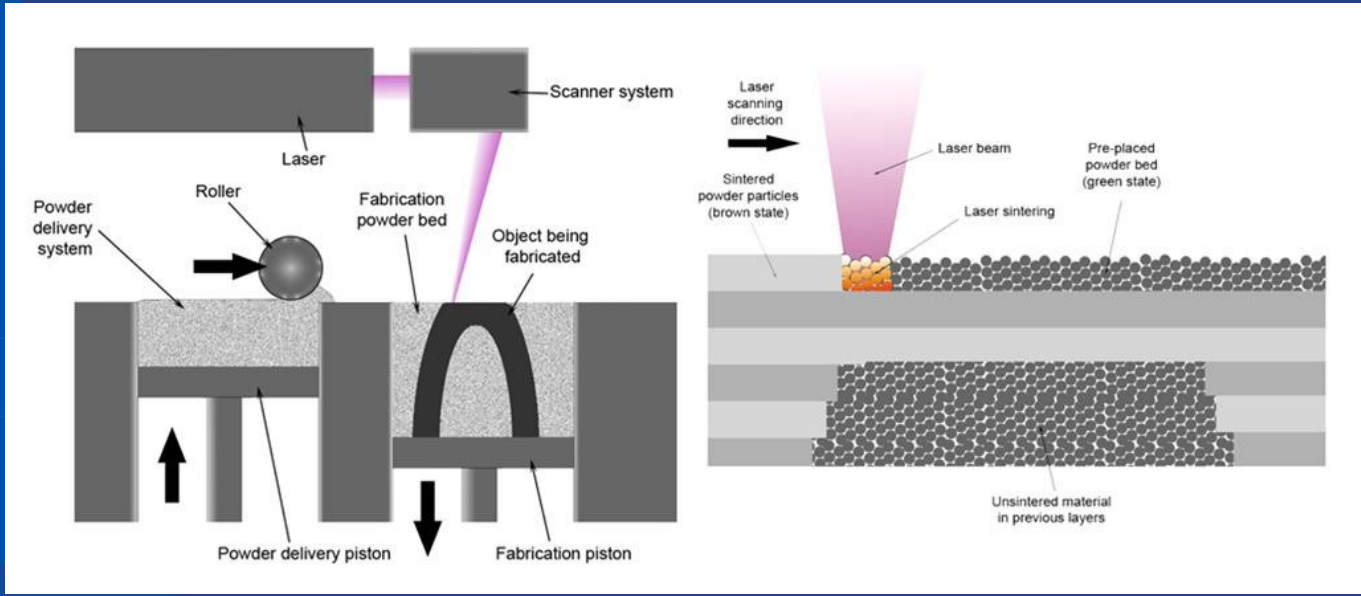


A. Anders, J. Vac. Sci. Technol. A 28 (2010) 783

- Zhou (J-Lab), with Alameda Applied Sciences: Nb films with RRR well above 300 attained for first time, Oct 2010
  - Flat films on hot sapphire
- Anders (LBL): HiPIMS system ready for cavities
- Do the new break-throughs make Nb/Cu or Nb/Al work for ILC?

Single-piece end groups

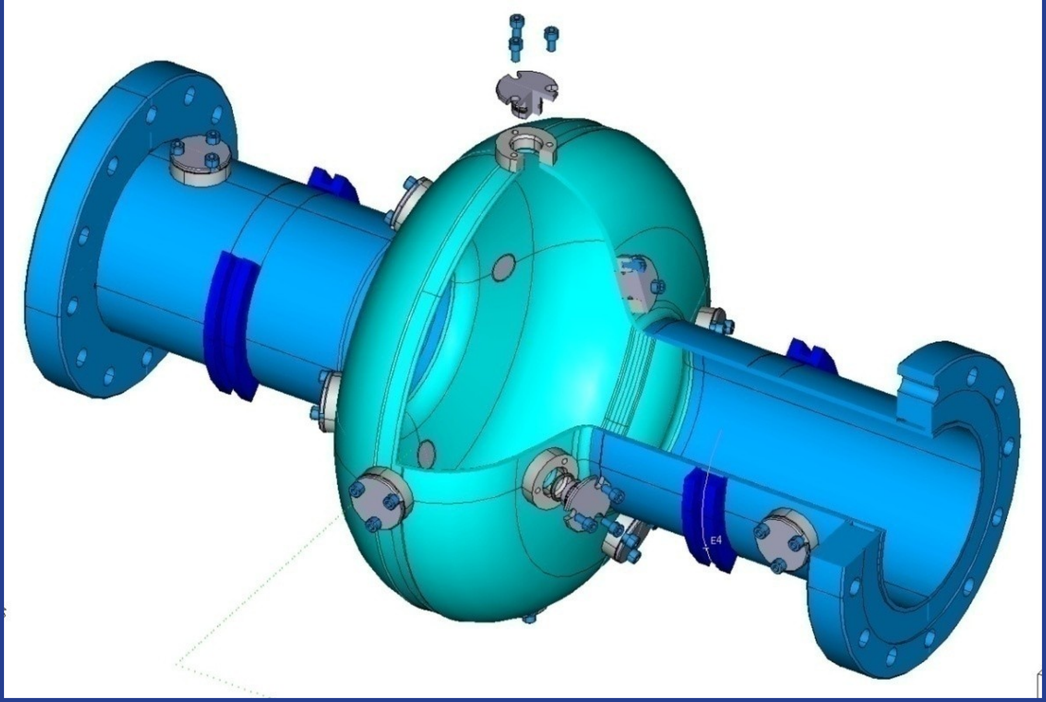
- India collaboration and Niowave have explored ideas to machine end group from Niobium blocks
- Additive machining – 3D "printing" from metal powders in vacuum, followed by sintering
  - Well established for complex titanium pieces
  - Niobium's challenges (high m.p., clean) could be met due to recent advances in equipment



All Labs should use coupon cavities

- Give materials scientists opportunities to provide process feedback without dissecting cavities
  - No other way to obtain spectroscopy from inside cavity
- Is a thick-wall version possible ?

C Cooper's design, similar to several others already being used



R&D MOTIVATED BY PHYSICS AND MATERIALS SCIENCE

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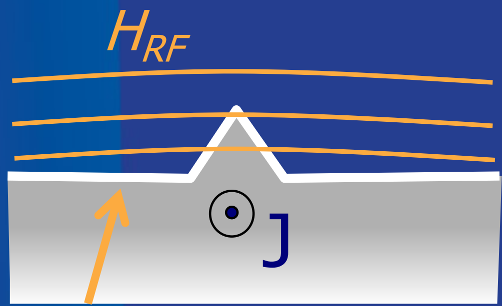
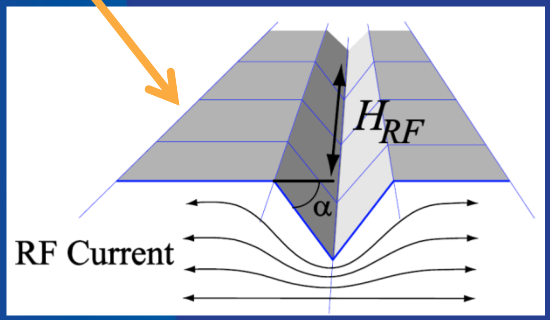
General aspects of the SRF surface



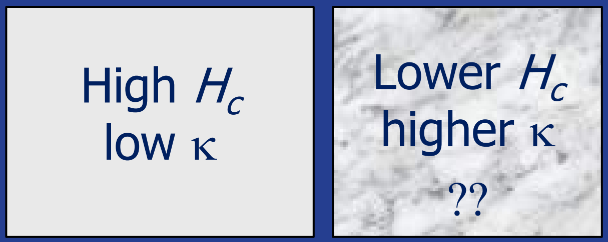
Knobloch et al

Surface Barrier

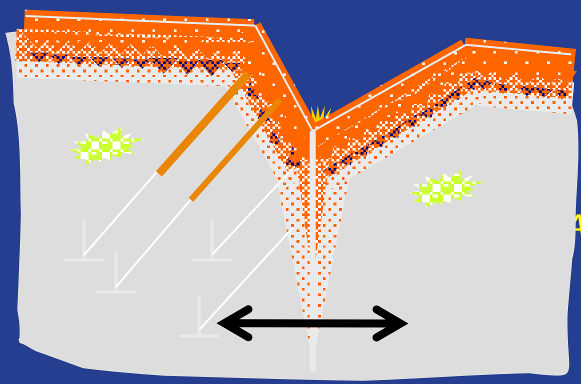


Dzyuba et al

RF flux should not penetrate due to topography: **Smoother surfaces are better** (but how smooth is smooth enough?)



Base superconducting properties should be ideal: **Less contamination**



Halbritter, Antoine, et al, Tian et al, Many others

RF current should not be induced across non- or weakly superconducting boundaries, precipitates, defects and damage: **Less contamination**

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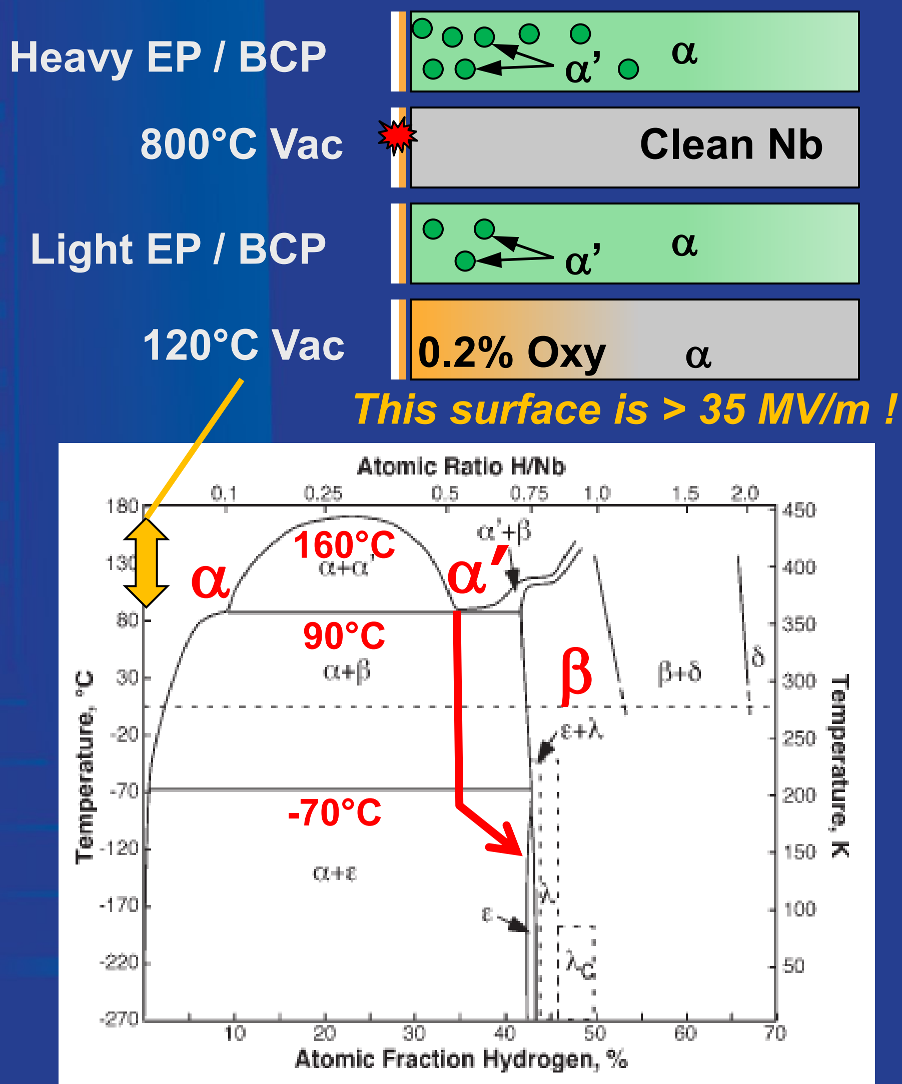
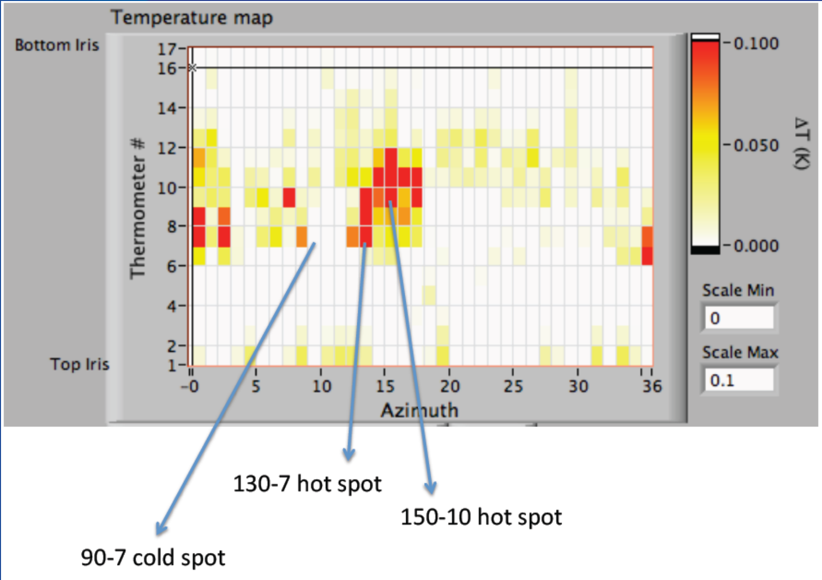
Latest models of the Nb surface region

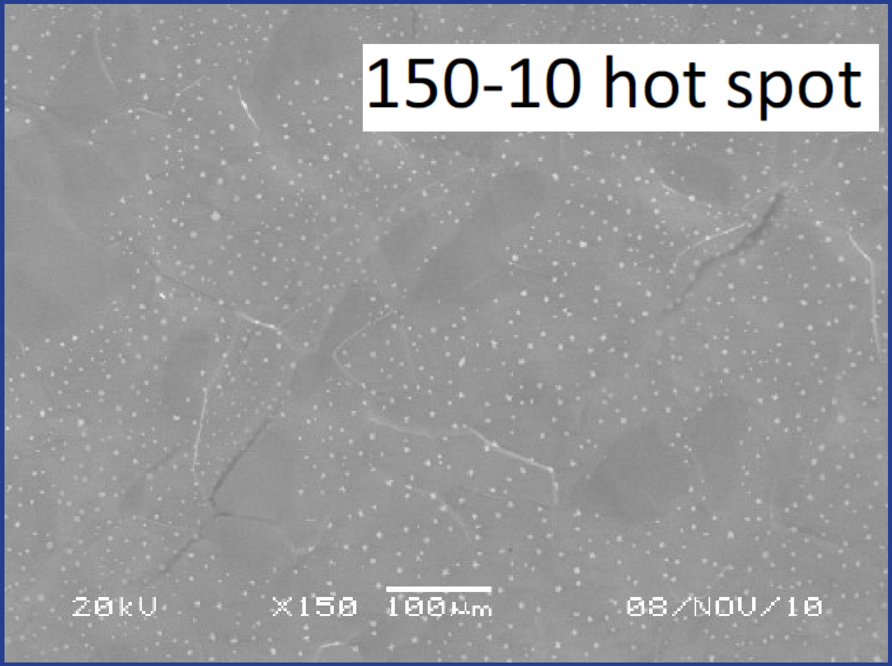


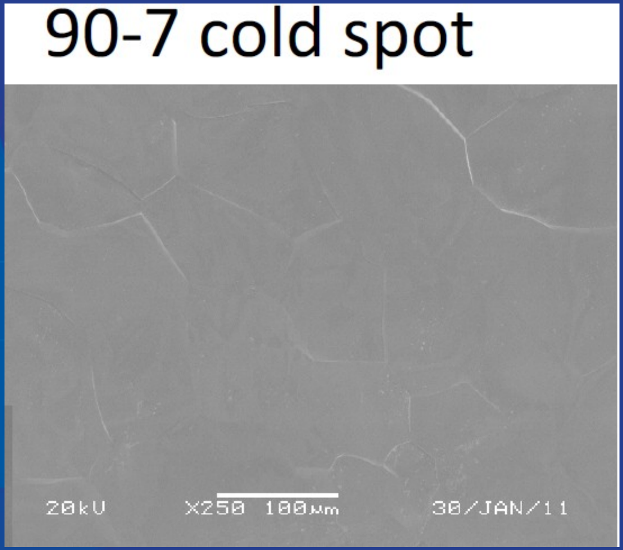
- 10-40% H at / under surface
  - BCP, EP, warm water …
  - $\alpha' \rightarrow \beta$
    - Nucleation on defects
    - What change after 800°C bake is more important: reduction of H or removed nucleation sites?
  - Lots of β: Q sickness
  - Some β: Q slope?
    - Are mid- and high-field Q slopes different aspects of same nanostructure?

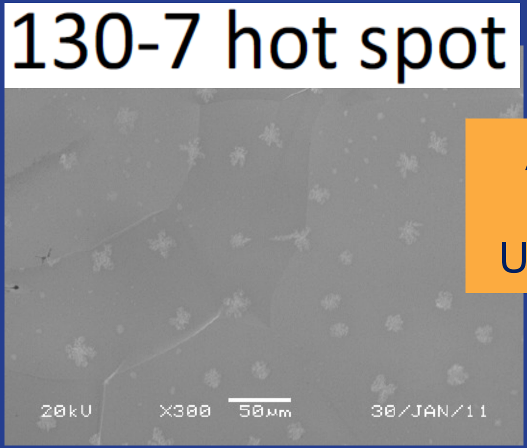
Ricker Myneni J.Res.NIST 2010
Ciovati – Ingot niobium workshop at J-Lab Sept 2010
Romanenko - He atom recoil spectroscopy with U.Mich. & W.Ontario

Possible connection between Q-slope (onset above 100 mT) and small near-surface precipitates









A. Romanenko, Fermilab, Unpublished work

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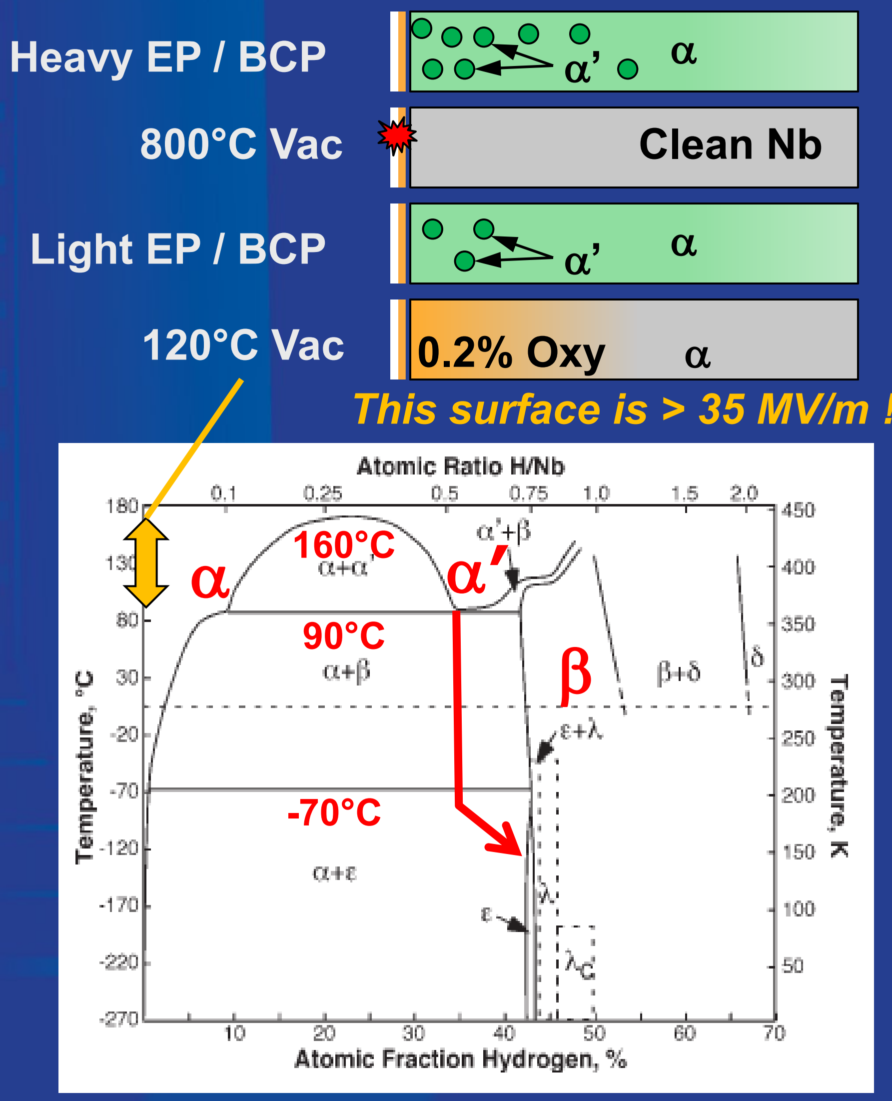
Latest models of the Nb surface region



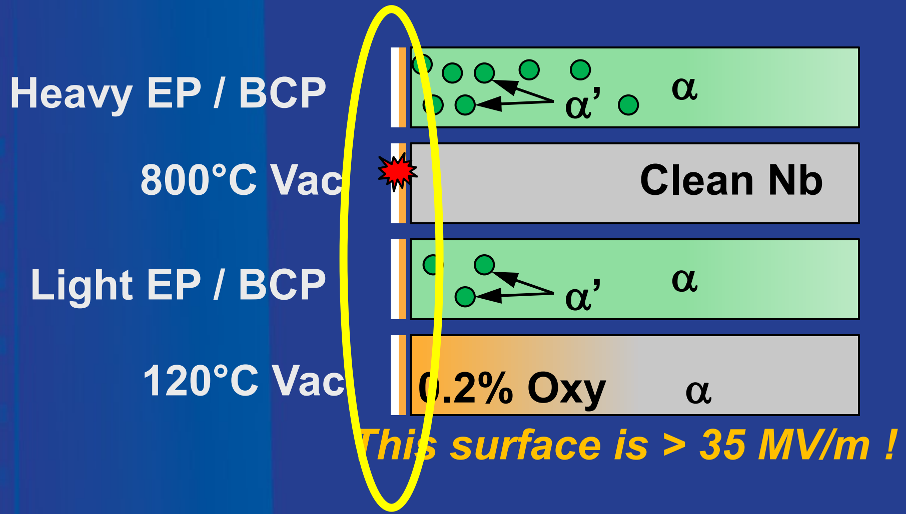
- 90°C to 160°C mobilizes H
  - H clusters (α′) disperse from vacancies, defects [1]
  - Oxygen enters from decomposition of surface oxide [2]
    - Does O bind to nucleation sites and disperse H, thereby suppressing β? [3]

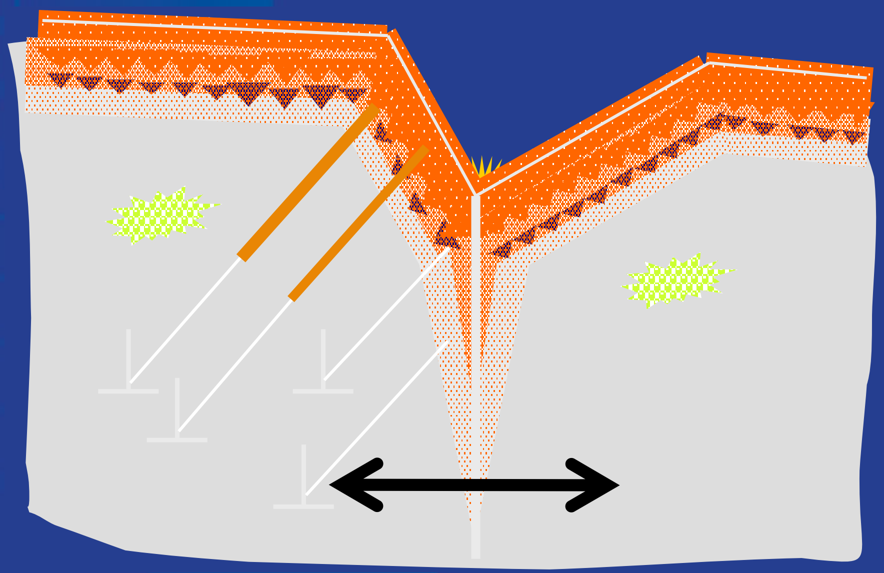
[1] Visentin et al, e+ / e- annihilation, SRF2009; Romanenko Ph.D. Thesis – Cornell,

[2] Casalbuoni et al, Nuc.Inst.Meth.PR-A 538, 45 (2005)

[3] D. Ford (NWU Ph.D. student) DFT + VASP at Fermilab

Latest models of the Nb surface region





- Nb-oxides contain magnetic defects [1,2]
  - Break Cooper pairs, reduce Q
  - Oxides are often amorphous[3], full of defects
  - Do dislocations transport magnetic ions inward?
- Are "wet" oxides worse than "dry" oxides?
  - Wet = water vapor, aqueous
  - H stabilizes O defects [2]

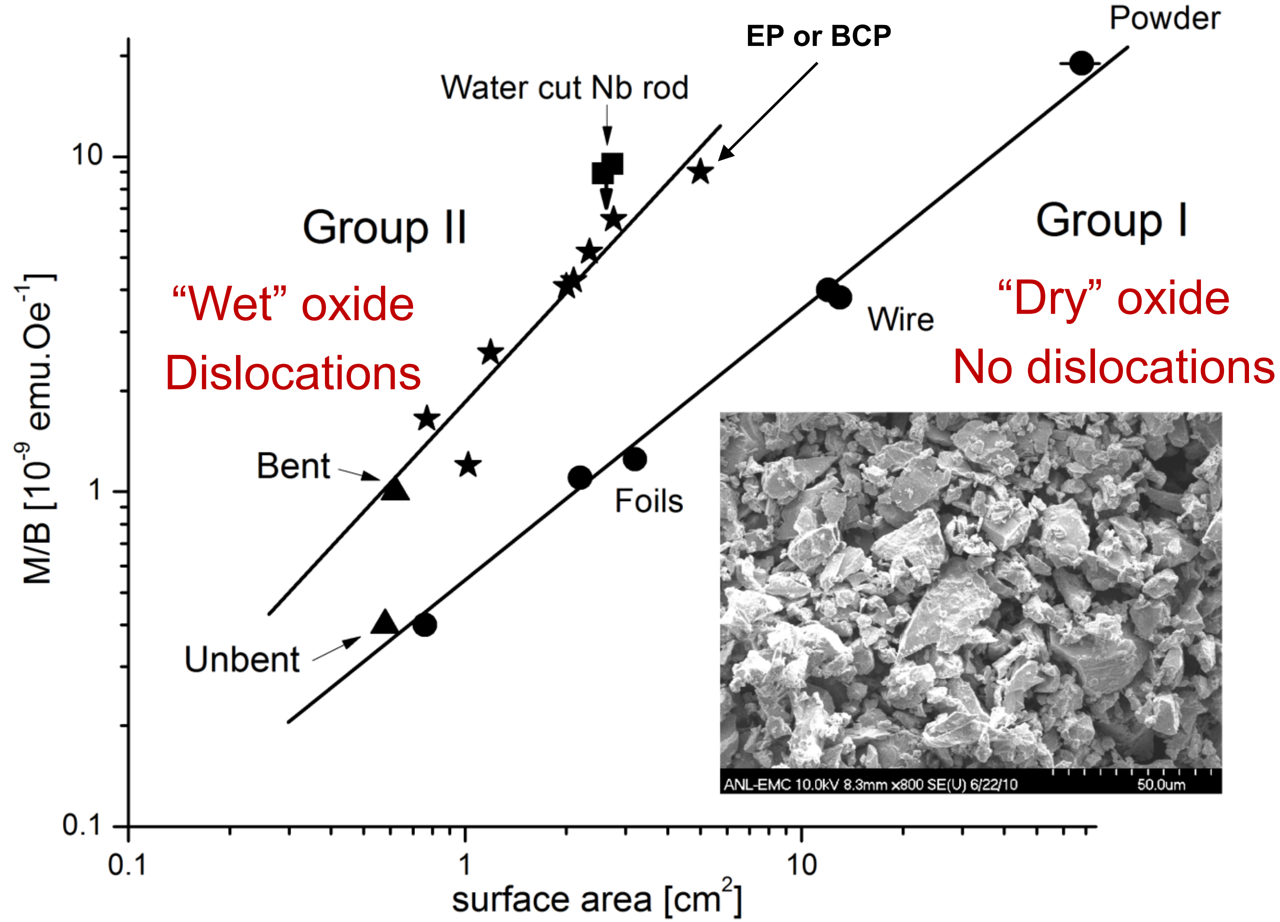
[1] Point-contact tunneling data: Zasadzinski group, IIT, and Prolier group, ANL, Appl. Phys. Lett. 2008, 2009.

[2] Density-functional calculations: W. Walkosz, ANL

[3] TEM data: R Klie, UIC

Dislocations affect magnetic signature

Slide Courtesy of T. Prolier, ANL and J. Zasadzinski, IIT



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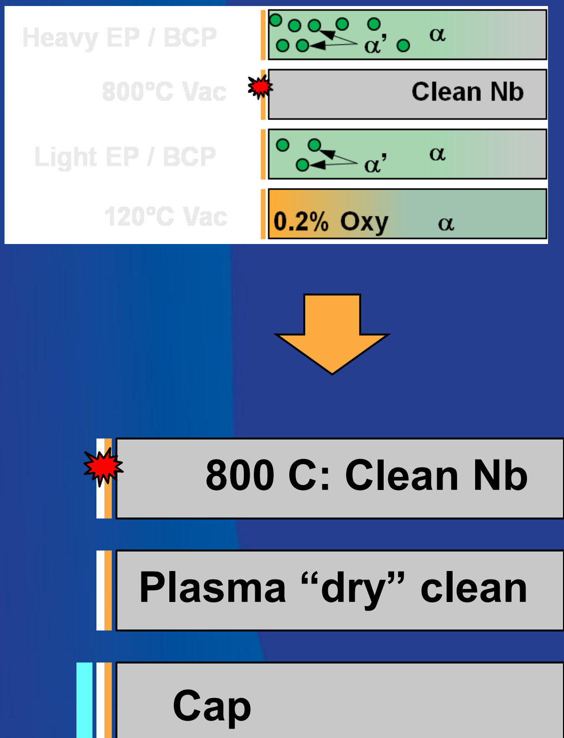
Implications for final processing R&D



No need for HPR?

- The 800°C high-vacuum anneal is a very important step
  - It erases side-effects of bulk removal
  - It forgives aspects of forming, welding
  - Are there better standards than time + temperature?
- Preserve the metal in this state
  - Low concentrations of O and H
  - Low concentrations of defects, nucleation centers, and dislocations
- Remove any debris by a dry technique, then cap immediately
  - Dry plasma cleaning
  - Dry deposition, e.g. modified ALD

Summary of R&D areas

- 9-cell Hydroforming
- Tubes for hydroforming
  - ATI Wah Chang product
  - Equal channel angular process
  - Zone annealing
- Tumbling
  - 4-step extension of CBP – ready to integrate with present process
  - Jump to mirror-smooth 5th step
    - As preparation for thin films
- Films & coatings
  - High power impulse sputtering
  - Dry etch, e.g. plasma cleaning
  - Dry protective coating, e.g. by Atomic Layer Deposition
  - Peel-off dust removal
- Coupon cavities
- 1-piece end groups

Possible processing baseline in 5 years

	Re-entrant (55 MV/m) Cavity Recipe
Fabrication	Nb tubes (Fine Grain)
	Single-piece end-group preparation
	Hydroform tubes and assemble end groups w/ EBW
Process	4-step Tumbling (Need to remove only ~ 50µm due to texture control)
	Ultrasonic degreasing with detergent, or ethanol rinse
	High-pressure pure-water rinsing
	Field flatness tuning
	Hydrogen degassing at > 800 °C
	Antenna Assembly
	Plasma Cleaning
	Capping by Atomic Layer Deposition
Vertical Test	Performance Test with temperature and mode measurement →inspection, reprocessing, other remediation

Industry

Inspection & remediation