Activities Directed Towards *Industrialization* of HF-FREE ElectroPolishing of Niobium SRF Cavities

Acid-Free Electropolishing of SRF Cavities
NP Phase II Grant No. DE-SC0011235

Faraday Technology, Inc.

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CRADA No. DE-AC05-06OR23177

Thomas Jefferson National Accelerator Facility

Hui Tian, PhD, Charles Reece, PhD

Cornell University

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August 8, 2018

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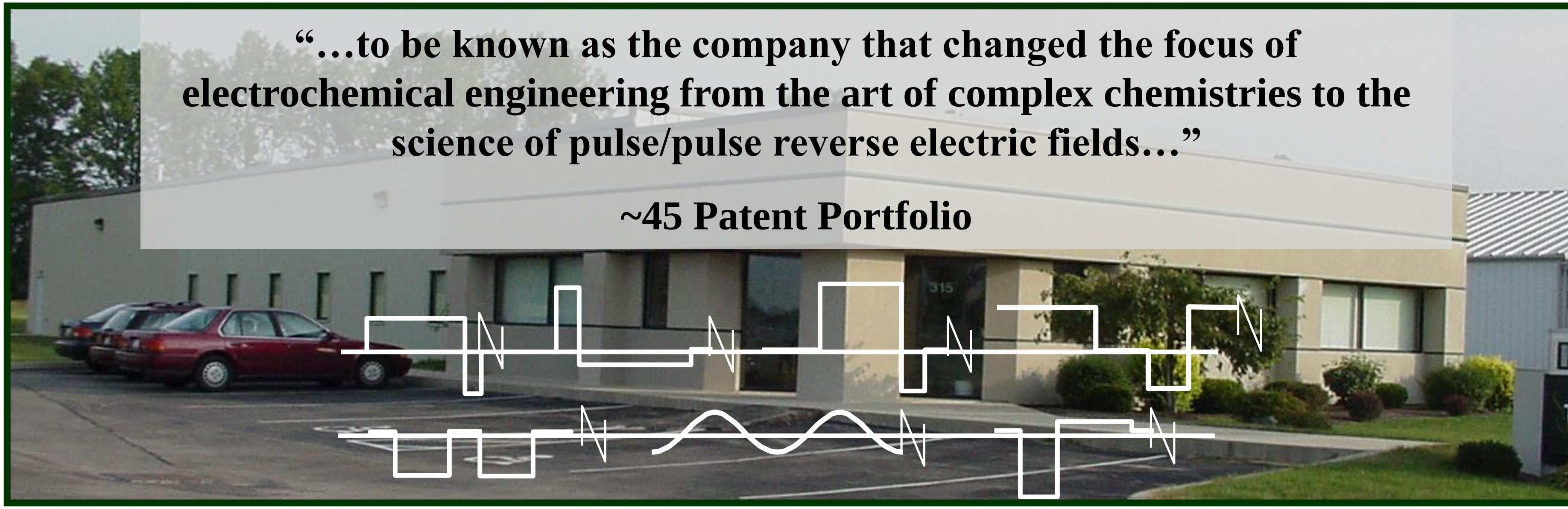
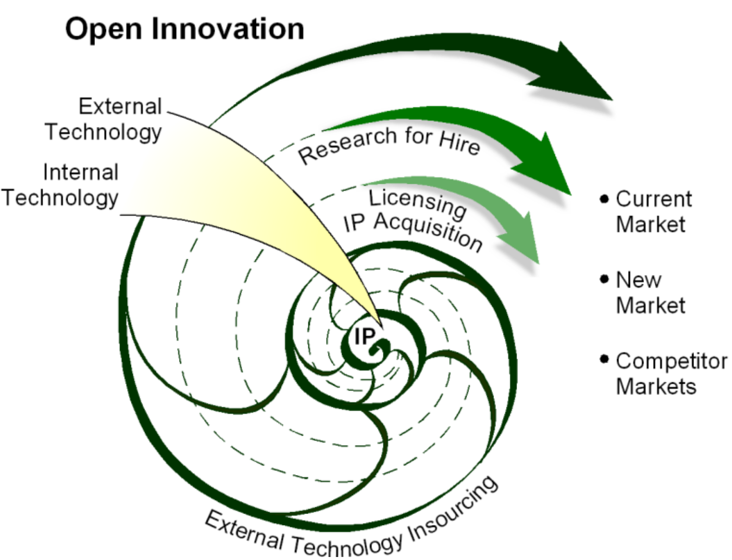
Company Overview: FARADAY TECHNOLOGY, INC.



- Electrochemical engineering processes and technologies – founded 1991
  - Pulse & pulse reverse electrolytic (polishing/plating) processes (in contrast to DC)
  - ~31 Issued US Patents, ~15 PCT Patents and ~15 Patents Pending
- Perspective
  - PhD in Electrochemical Kinetics (on-site at Brookhaven National Lab/UVA)
  - MS in Technology Strategy,
  - Patent Bar

www.FaradayTechnology.com

Commercialization Model: Open Innovation



Development of robust process is critical!

- Leverage Federal SBIR opportunities as non-equity technology funding
  - Establish IP rights (31 US patents issued)
    - ✓ 2 US, Japanese, European
- Collaborate with universities/government laboratories
  - TJNAF, KEK, Cornell, FNAF
- Develop electrochemical engineering solutions based on PC/PRC processes
  - FARADAYIC® HF-FREE ElectroPolishing
- Industrialization: Transition of EP technology
  - DEM/VAL
    - ✓ α-scale at Faraday
    - ✓ β-scale at TJNAF, KEK, metal finishing company
  - Become defined "Build to Print & Process"
  - Geographic "jump start" license
    - ✓ Japan metal finishing (Marui, Nomura, Mitsubishi)
    - ✓ Europe metal finishing industry
  - Faraday US production – then license for volume
    - ✓ US metal finishing (TechMetals, ABLE EP)

➔ Key: TJNAF (FNAF) define *"Build to Print & Process"*

Opportunity: SRF Niobium Cavity Electropolishing (EP)

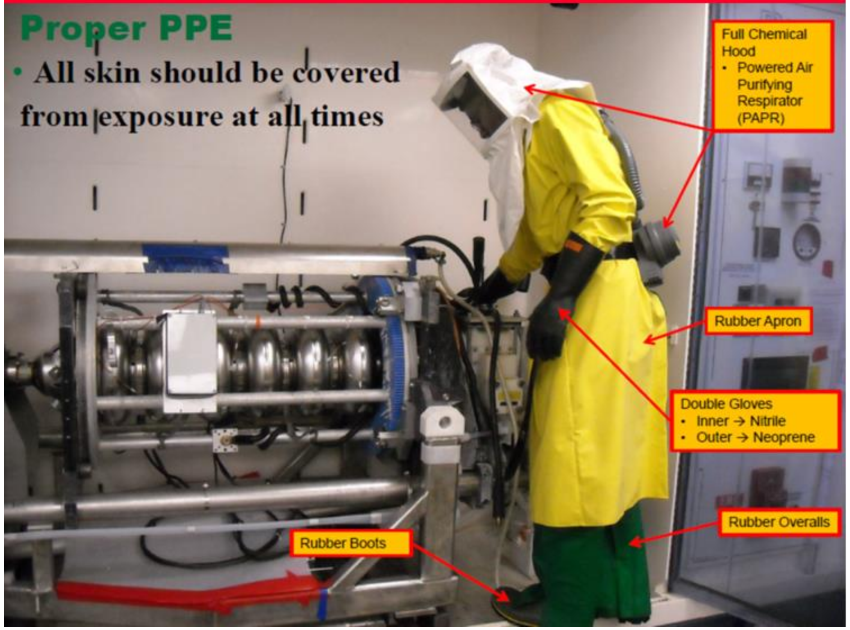
Nb Superconducting Radio Frequency (SRF) are required for the International Linear Collider as well as other high energy physics projects. To achieve required particle acceleration gradients, electropolishing is the final surface finishing operation;

9:1 H_2SO_4 (98%) : HF(48%) electrolyte (DC) "High Viscosity"

"…well known… viscous salt film paradigm"

H_2SO_4/HF ➔ Highly Corrosive!
HF ➔ Extremely Hazardous!
➔ Safety/Cost Burden!

Personal Protective Equipment (PPE) for "conventional" SRF niobium cavity electropolishing using sulfuric acid – hydrofluoric acid mixture.
John Mammosser, Instructor
"Chemical Safety for SRF Work"
U.S. Particle Accelerator School
January 2015



T. Dote, K. Kono(2004), "An Acute Lethal Case of Exposure During A Washing Down Operation of A Hydrogen Fluoride Liquefying Tank", *Japanese Journal of Occupational Medicine and Traumatology*, **52**, 3, pp189-192.

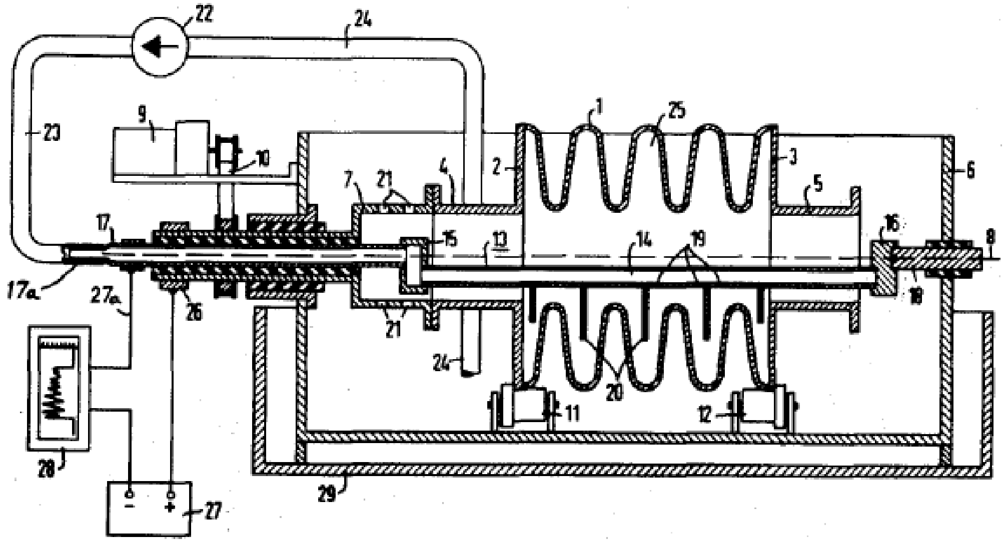
U.S. Pat. No. 4,014,765 - Siemens 1977

Problem of …

"…electrolytic polishing hollow niobium bodies of a ***complicated geometrical structure****…where development of gases…rise from the cathode…forming* ***gas pockets****…resulting in portions of the* ***inside surface not polished****…"*

…is solved by…

"…***horizontally orienting*** the hollow niobium ***body…partially filling*** said hollow body with polishing solution and slowly ***rotating*** said hollow body…"



Note;
electrode "fins" to level current distribution disclosed – only recently considered by the particle physics community?

➔ *Horizontal operation adds significant CapEx investment in cavity processing tools and OpEx cost in addition to safety burden!*

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Pulse Reverse EP Process

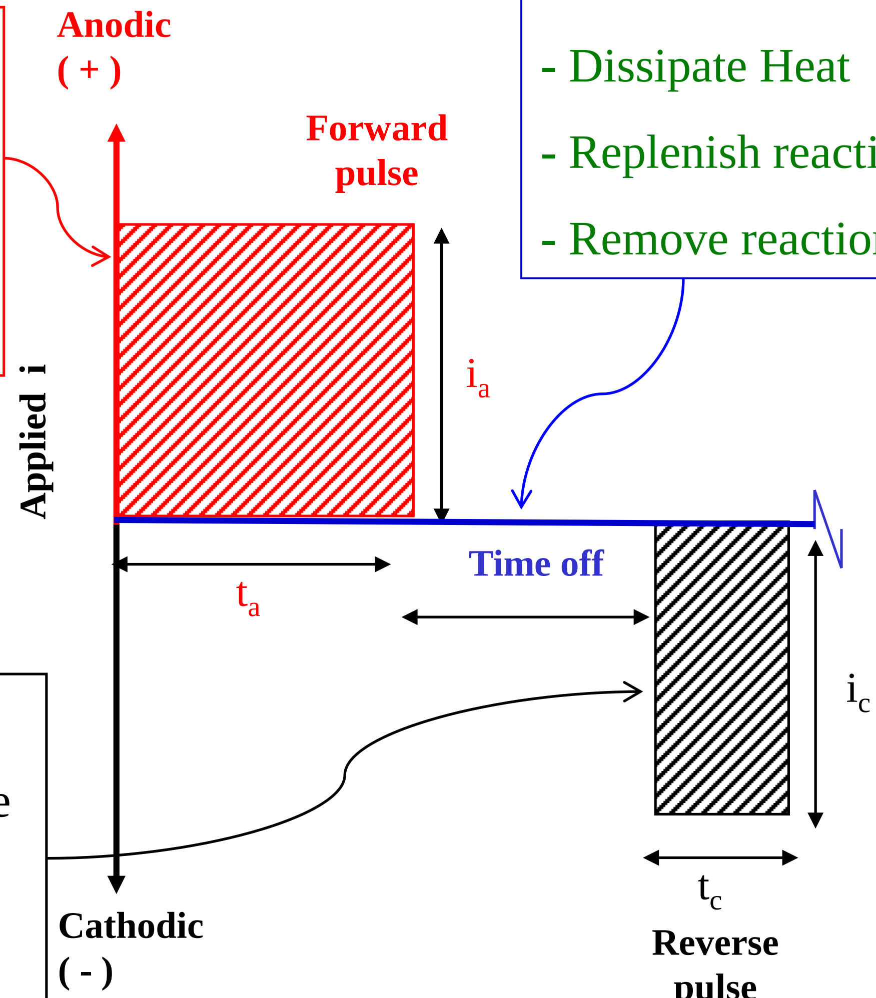
Anodic Pulse “Tuned” to:

- Focus current distribution

➔ Eliminates need for viscous electrolytes, i.e. concentrated H_2SO_4

Off-Time “Tuned” to:

- Dissipate Heat
- Replenish reacting species
- Remove reaction products



Cathodic Pulse “Tuned” to:

- Depassivate surface/remove oxide

➔ Eliminate need for HF, and/or low water content electrolytes?

Not all waveforms work for a given application!
➔ need guidance!

FARADAYIC® HF-FREE EP = Bipolar EP

Pulse Reverse EP Studies

- 3 wt% H_2SO_4 in H_2O (NO HF)
- Vertical (electrolyte "dump" mode)
- 100% Volume Fill
- No Rotation

➔ Analogous to plating of IDs
➔ Simpler/Industrial Compatible

➔ *Enabled by low viscosity electrolyte!* 🡐

ILC Machine Staging report,
"The change in the SC-cavity chemical treatment from using Horizontal electropolishing (EP) and Sulphur-acid+HF…, to Vertical EP + non-HF solution + Bipolar EP, will lead to substantial process cost reduction…simpler infrastructure, shorter processing time, cheaper solution, cheaper solution waste process, and a safer process without HF."

Takayuki Saeki (KEK),
"… the Bipolar EP process is the most promising technology for cavity mass-production and your company[Faraday] *is the pioneer for this technology."*

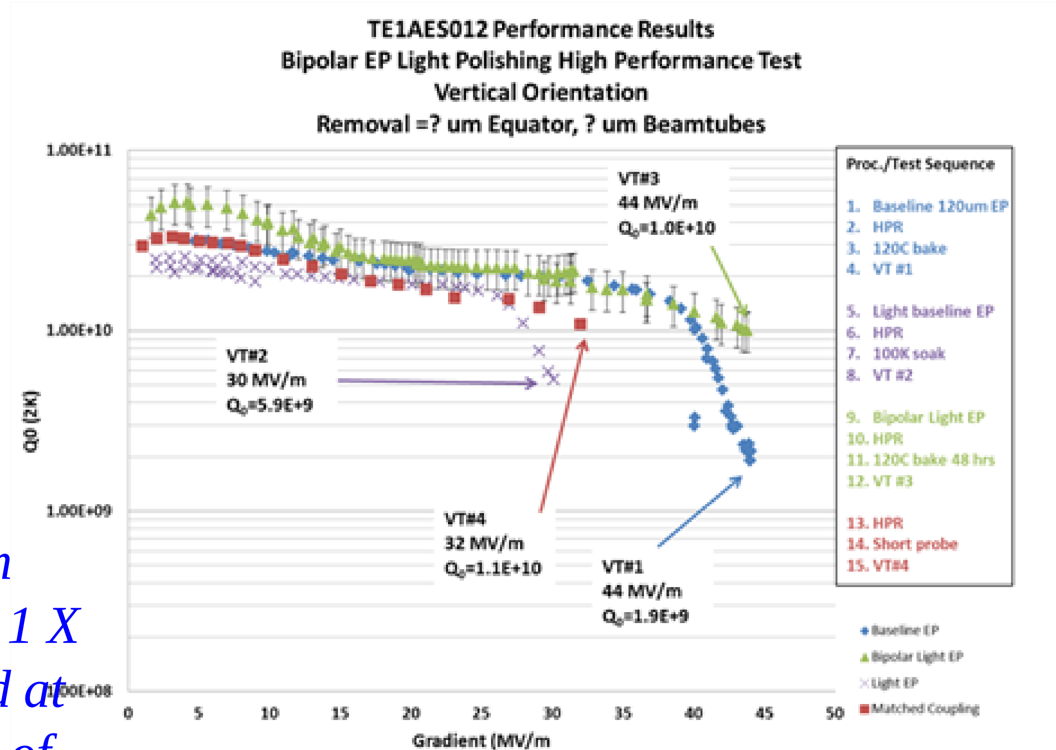
Single Cell Cavity – TE1AES012

"BiPolar EP" (PRC)

- Vertical
- 100% Volume Fill
- No Rotation
- 10 wt% H_2SO_4 in H_2O

➔ 25 µm removed "light EP"

"…Cavity achieved a maximum gradient of ~44 MV/m with a Q_0 of 1 X 10^{10}, the highest gradient observed at Fermilab in any cavity regardless of processing technique…"



[†]E.J. Taylor, T.D. Hall, M. Inman, S. Snyder "Electropolishing of Niobium SRF Cavities in Low Viscosity Aqueous Electrolytes without Hydroflouric Acid" Paper No. TUP054, Presented SRF2013, Paris, FRANCE Sept. 2013.

[†]A.M. Rowe, A. Grassellino, T.D. Hall, M.E. Inman, S.T. Snyder, E.J. Taylor "Bipolar EP: Electropolishing without Flourine in a Water Based Electrolyte" Paper No. TUIOC02, Presented SRF2013, Paris, FRANCE, 2013.

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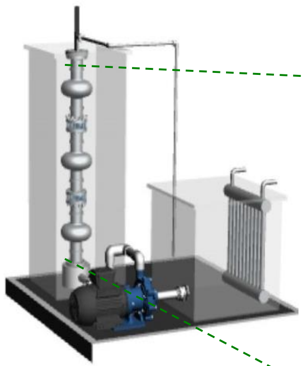
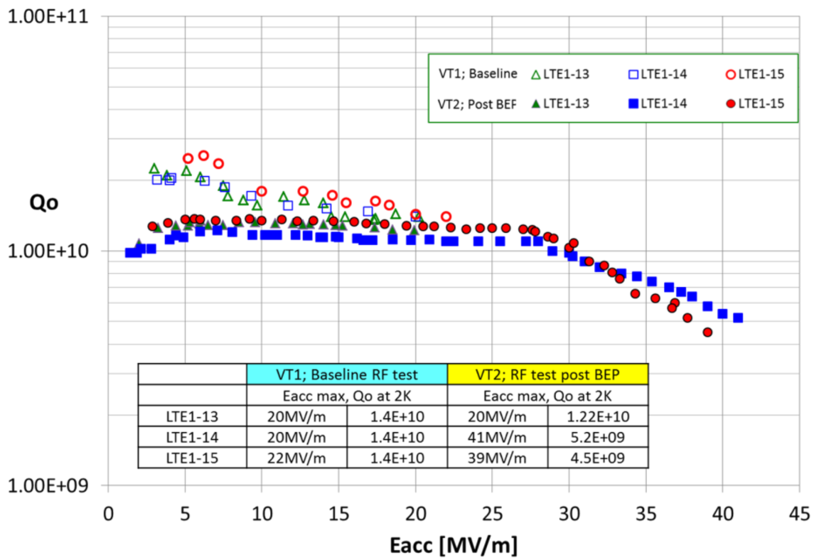
3 Stacked 1-Cell/3-Cell Cavities

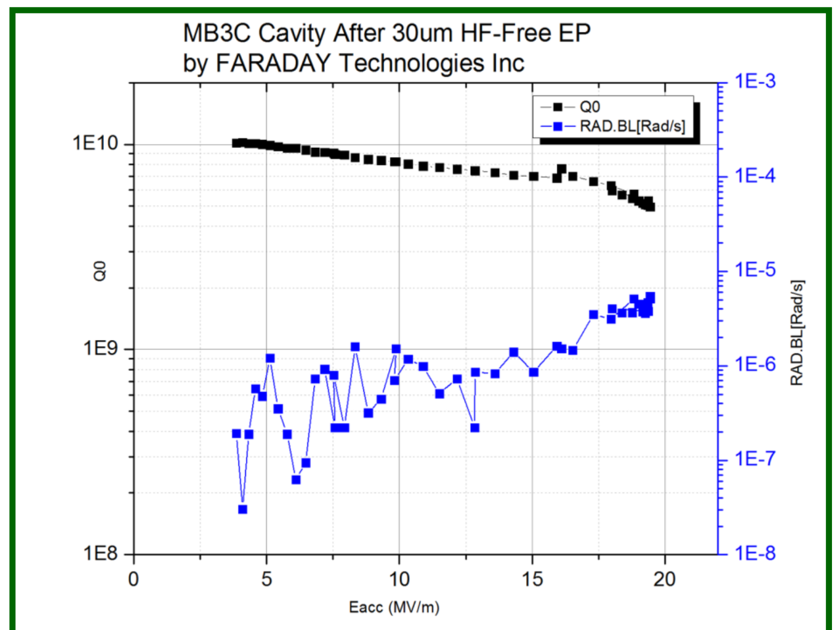


Oak Ridge National Laboratory

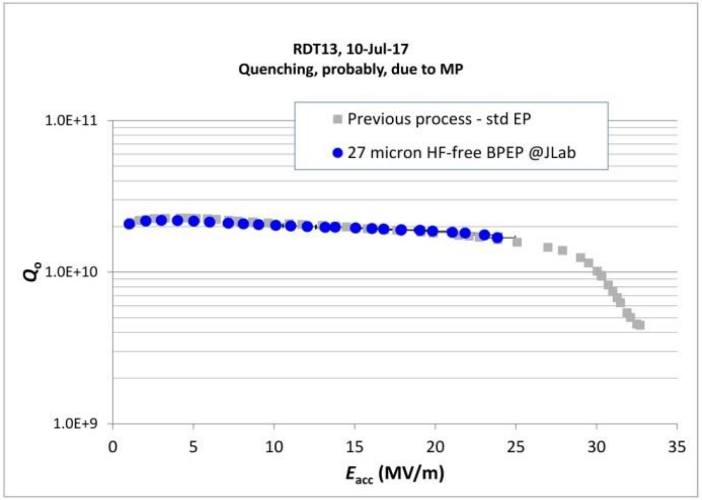
"…very good results." J. Mammosser
Prototype Medium Beta 0.61 805MHz for SNS



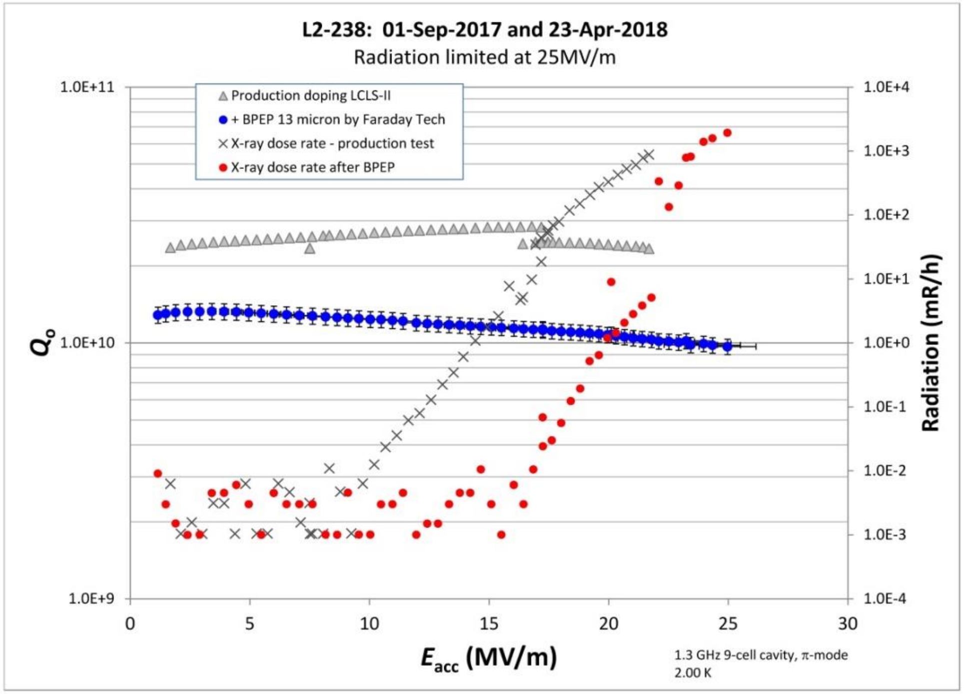
	VT1; Baseline RF test		VT2; RF test post BEP	
	Eacc max, Qo at 2K		Eacc max, Qo at 2K	
LTE1-13	20MV/m	1.4E+10	20MV/m	1.22E+10
LTE1-14	20MV/m	1.4E+10	41MV/m	5.2E+09
LTE1-15	22MV/m	1.4E+10	39MV/m	4.5E+09



1-Cell/N_2 1-Cell/9-Cell Cavities



- 1-Cell Cavity β-Test at JLAB using Faraday Parameters
  - JLAB home grown rectifier (L. Phillips/C. Reece)
  - Equivalent performance (C. Reece)
- 1-Cell Cavity N_2 “Doped” processed at Faraday
  - Equivalent performance (Not Shown)(C. Reece)
- 9-Cell Cavity processed at Faraday
  - Highest performance for this cavity 32 MV/m
  - Radiation limited due to contaminant (C. Reece)



Jefferson Lab
Thomas Jefferson National Accelerator Facility

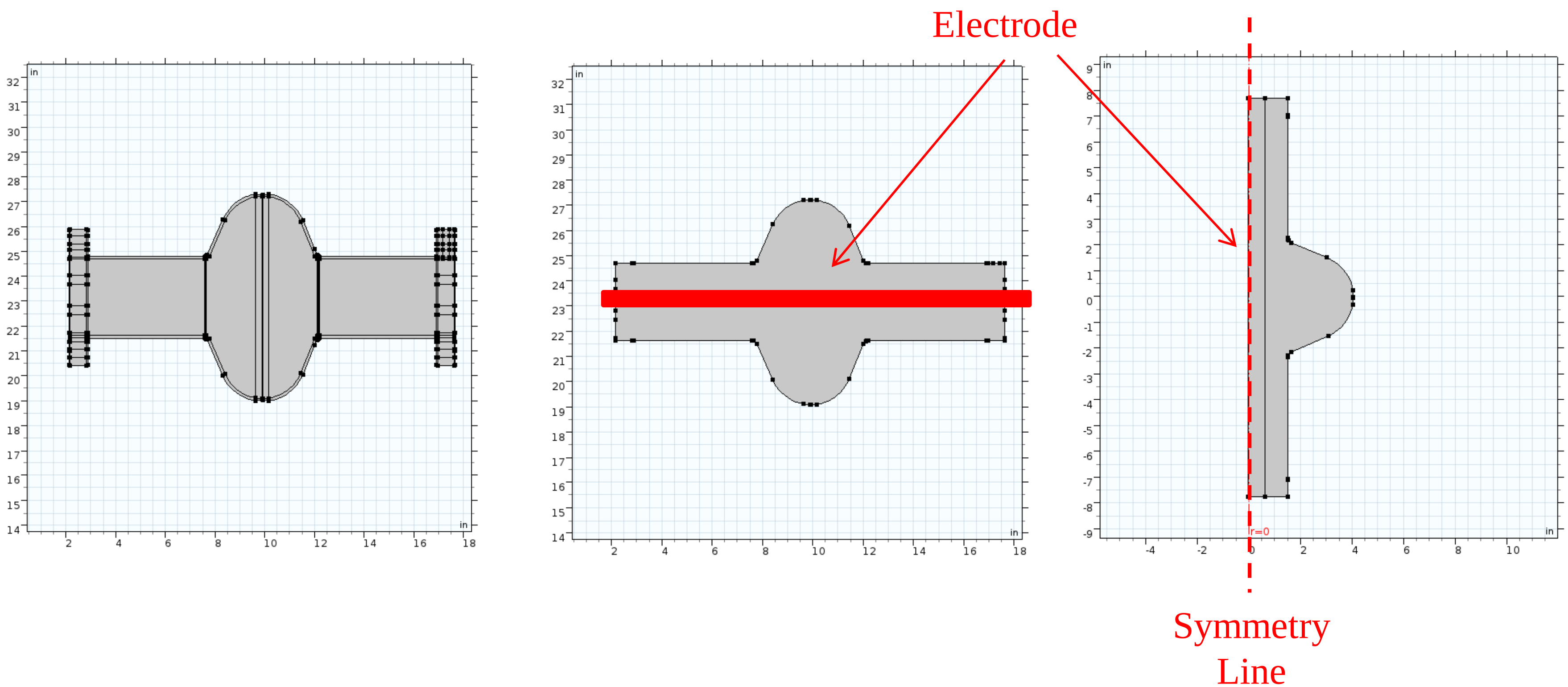
KEK
INTER-UNIVERSITY RESEARCH INSTITUTE CORPORATION
HIGH ENERGY ACCELERATOR RESEARCH ORGANIZATION

COMSOL: Current Distribution & Flow

FARADAY TECHNOLOGY, INC.

- Current distribution & electrolyte flow impact electropolishing uniformity
  - Current EP process: Direct Current (DC) H_2SO_4 – HF
  - FARADAYIC® HF-FREE (BiPolar) EP: pulse reverse H_2SO_4 – H_2O

→ Import CAD into COMSOL → Incorporate electrode and define symmetry



Current Distribution → Material Removal

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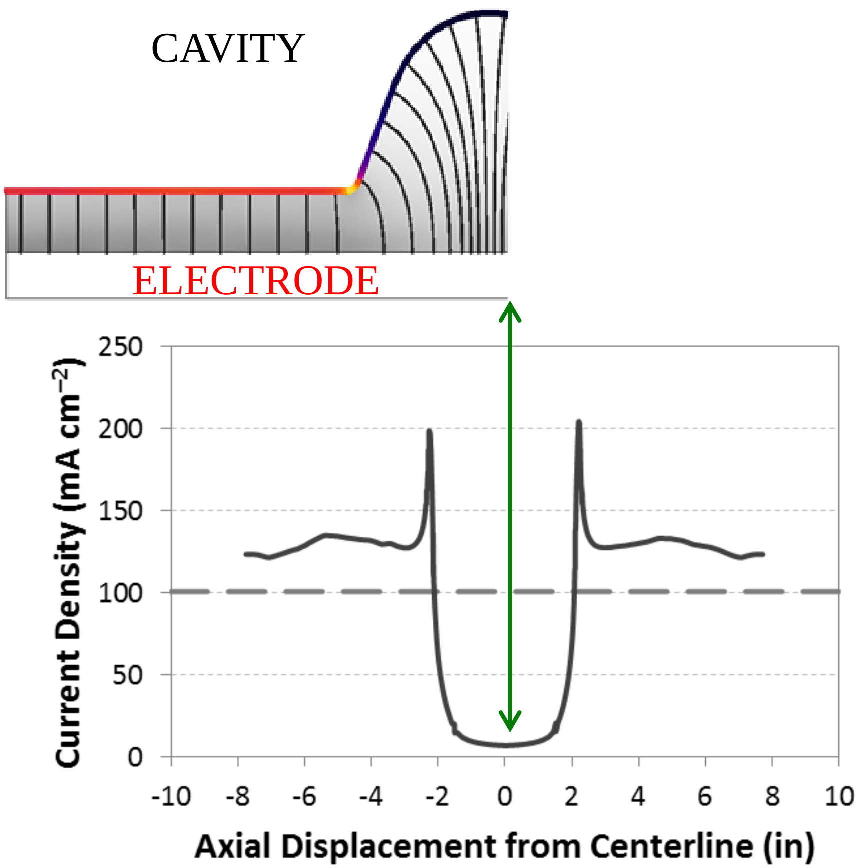
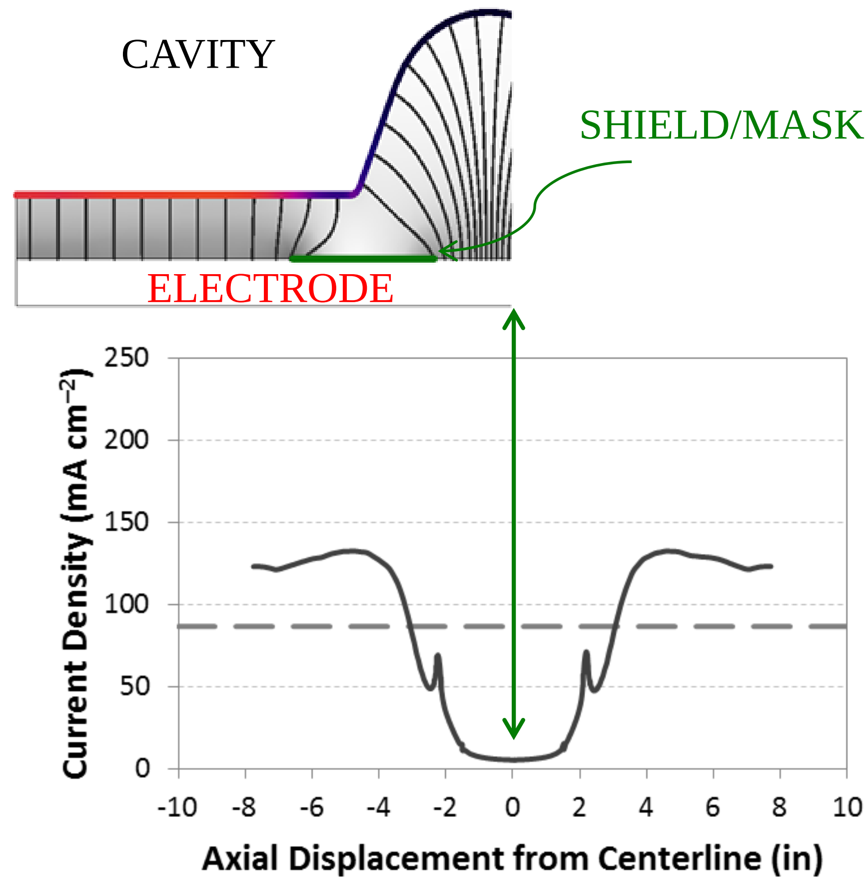
NO SHIELD/MASK



CURRENT DISTRIBUTION – MATERIAL REMOVAL

WITH SHIELD/MASK



CURRENT DISTRIBUTION – MATERIAL REMOVAL

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Flow Distribution: Conical Baffle

Low Baffle

Middle Baffle

Conical Baffle

Low Baffle

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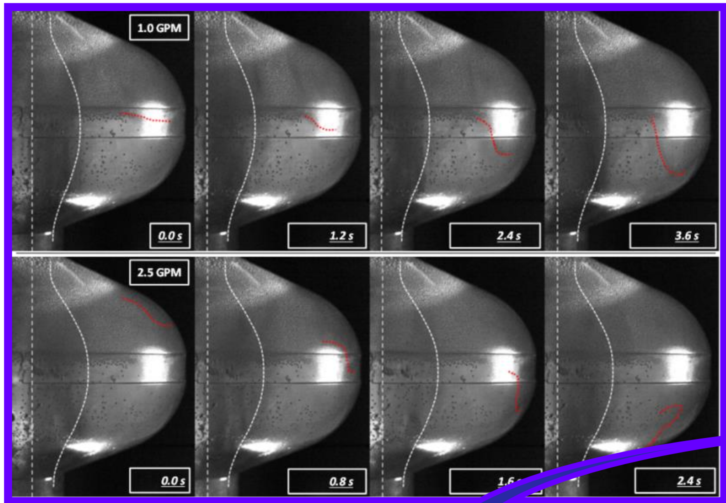
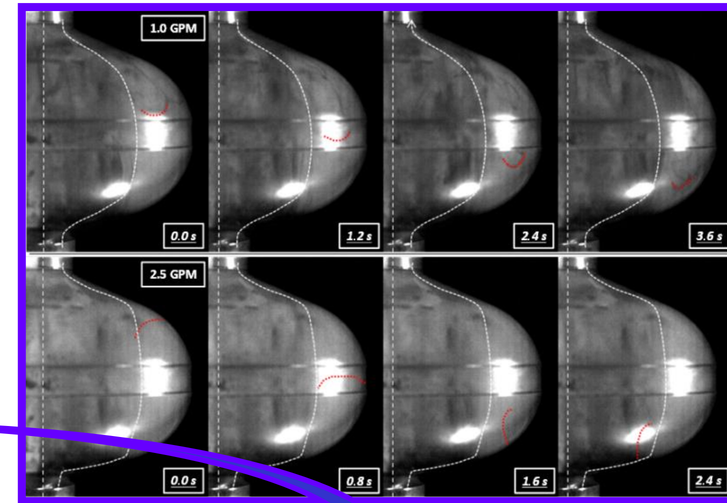
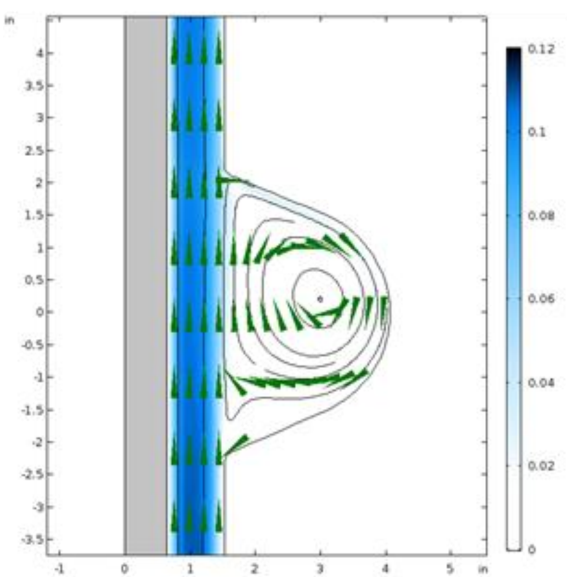
Flow Distribution: Conical Baffle



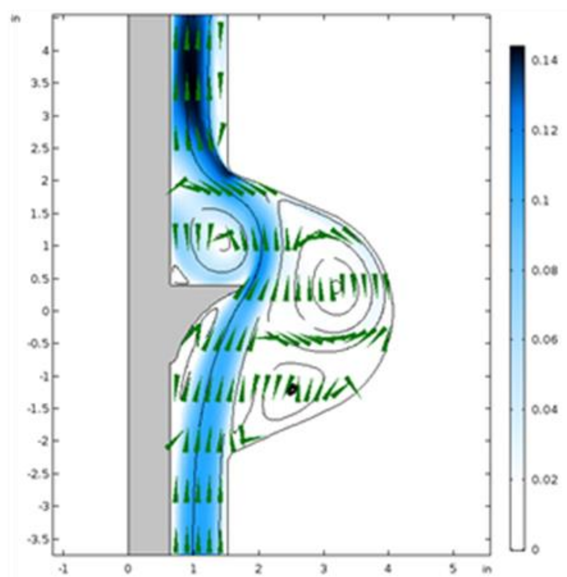
High speed video confirmation



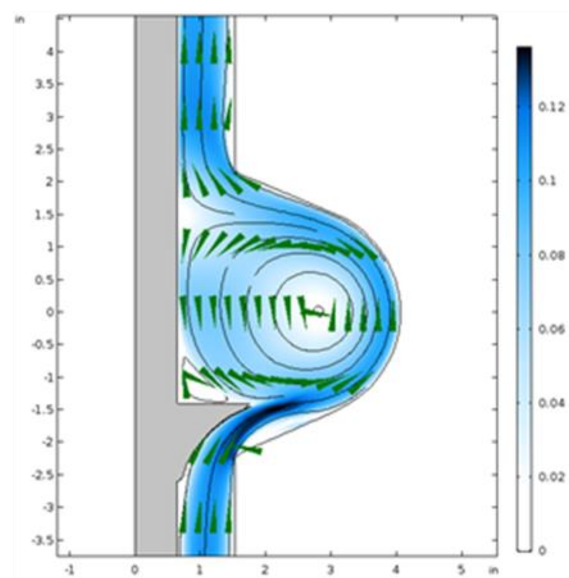
No Baffle



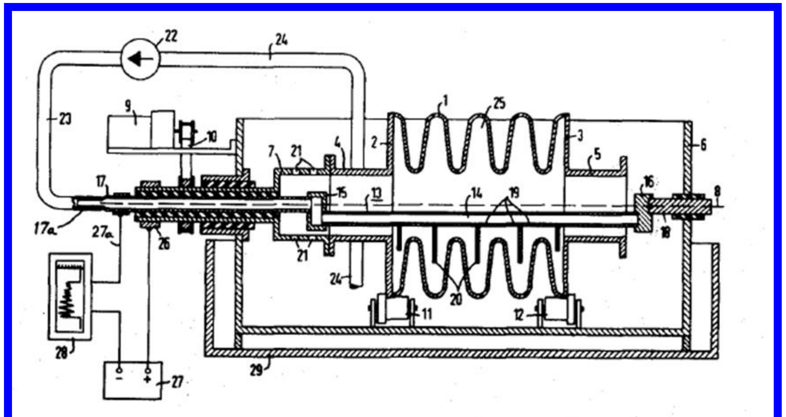
Middle Baffle



Low Baffle



Commercialization: IP Strategy



Prior Art (Seimens)

"Method for the electrolytic polishing of the insdie surface hollow niobium bodies"
U.S. Patent No. 4,014,765 issued March 29, 1977.

Viscous electrolyte (9:1 H_2SO_4 : HF)
- Horizontal orientation
- Partially filled
- Rotation

➔ Challenge for industrialization
- Electrolyte safety
- High CapEx and OpEx

Intellectual Property Portfolio
- FARADAYIC® registered
  - Trademark Reg. No. 3,178,757
  - Service mark Reg. No. 3,423,999
- FARADAYIC® HF-FREE EP
  - U.S. Pat. No. 9,006,147 4/14/2015
  - Jap Pat. No. 6,023,323 10/14/ 2016
  - EP Pat. No. 2,849,908 1/15/2017
    France, Germany, Italy, Switzerland, United Kingdom
  - U.S. Pat. No. 9,987,699 6/5/2018

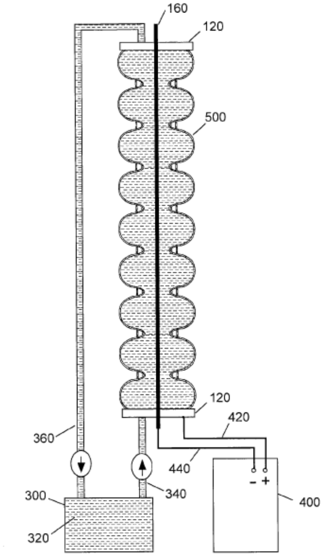


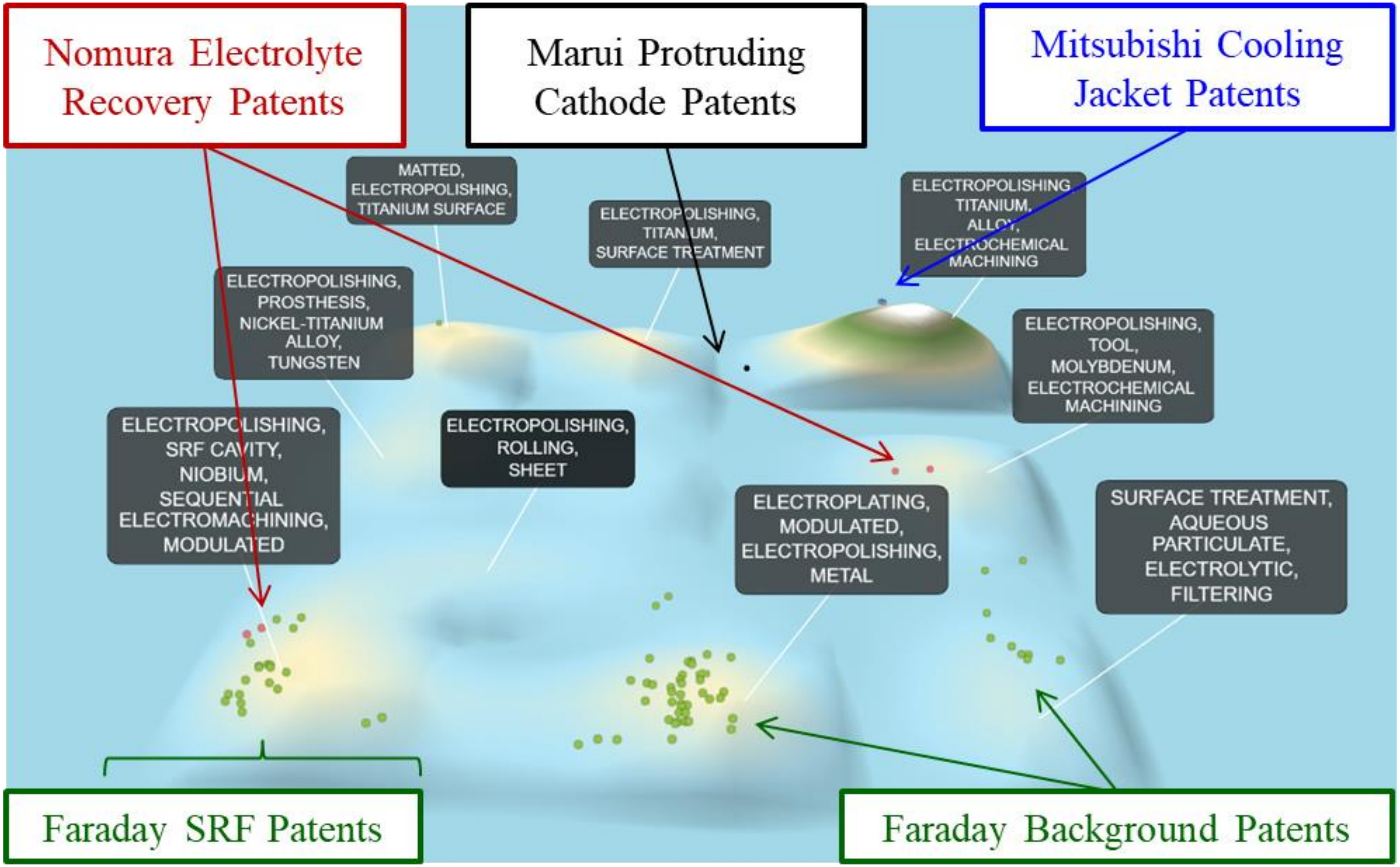
Fig. 12

- Independent claim directed towards low viscosity!!

➔ Low concentration – aqueous electrolyte (acid/alkaline)
- ✓ Vertical orientation
- ✓ Completely filled
- ✓ No rotation

➔ Industrially compatible – metal finishing value chain
- ✓ Safe
- ✓ Low CapEx and OpEx

Commercialization: Synergistic IP?



- Independent claim directed towards low viscosity!!
- Strong patent cluster
- Synergistic with recent art (Marui/Mitsubishi)

Prior Industrialization Attempts: HF-Based EP

- ABLE ElectroPolishing – Metal Finishing Supply Chain
  - FNAF & TJNAF *"transferred"* via *"Build to Print & Process"* protocol
  - Protocol outside the *"normal"* practice
    - ✓ Extensive training
    - ✓ CapEx safety precautions
  - Lack of experience & education of existing staff
    - ✓ Few if any staff have B.S. degree

➔ Lack of *"consistent"* SRF cavity revenue to support *"additional specialized"* staff 🡐

- Advanced Energy Systems (AES) – "Stand-Up Company"
  - FNAF *"transferred"* via *"Build to Print & Process"* protocol
  - FNAF paid for infrastructure CapEx (ARRA)
  - Highly skilled/educated staff
    - ✓ Successful technology transfer
  - Dependent on SRF cavity revenue

➔ Lack of *"consistent"* SRF cavity revenue to support of *"specialized"* staff 🡐

Industrialization: BiPolar HF-FREE EP

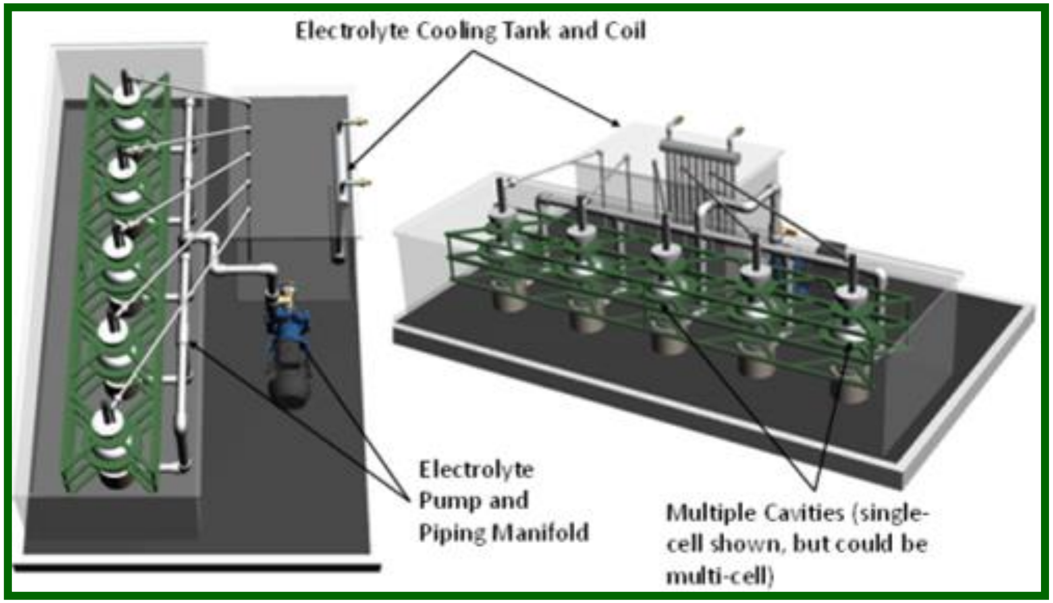
"…[BiPolar EP//FARADAYIC HF-FREE® EP] …*is no more hazardous or ecologically unfriendly than a household cleaner…*"

Alan Rowe, FNAF

- Metal Finishing Supply Chain
  - Technology *"transfer"* via *"Build to Print & Process"* protocol
  - Protocol within *"normal"* practice
    - ✓ Extensive training NOT required
    - ✓ NO additional CapEx or safety precautions required
  - Sufficient experience & education of existing staff

➔ SRF cavity revenue "*supplements*" existing revenue, NOT dependent on SRF cavity revenue 🡐

"Industrial" process analogous to plating (electrodeposition) of internal diameters such as those used in aerospace industry.



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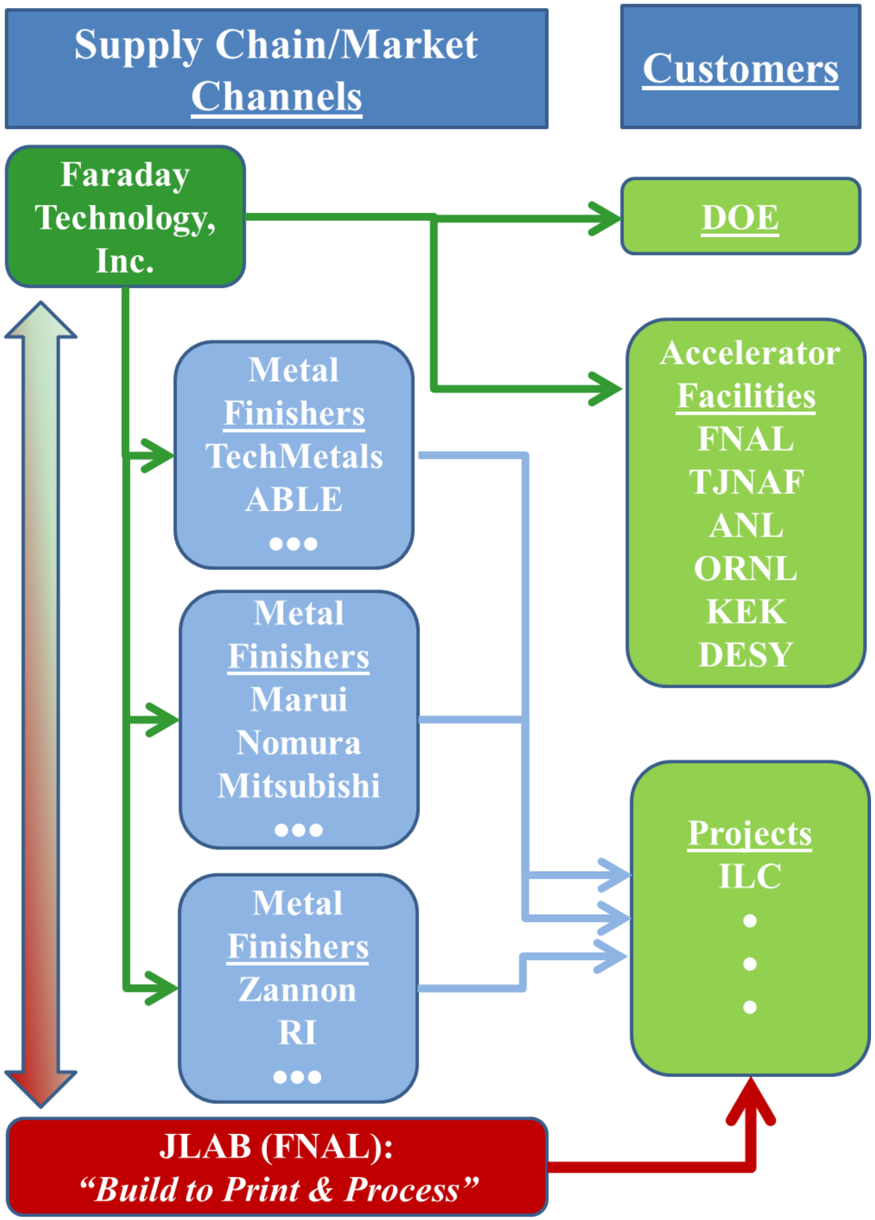
Commercialization: Value Chain



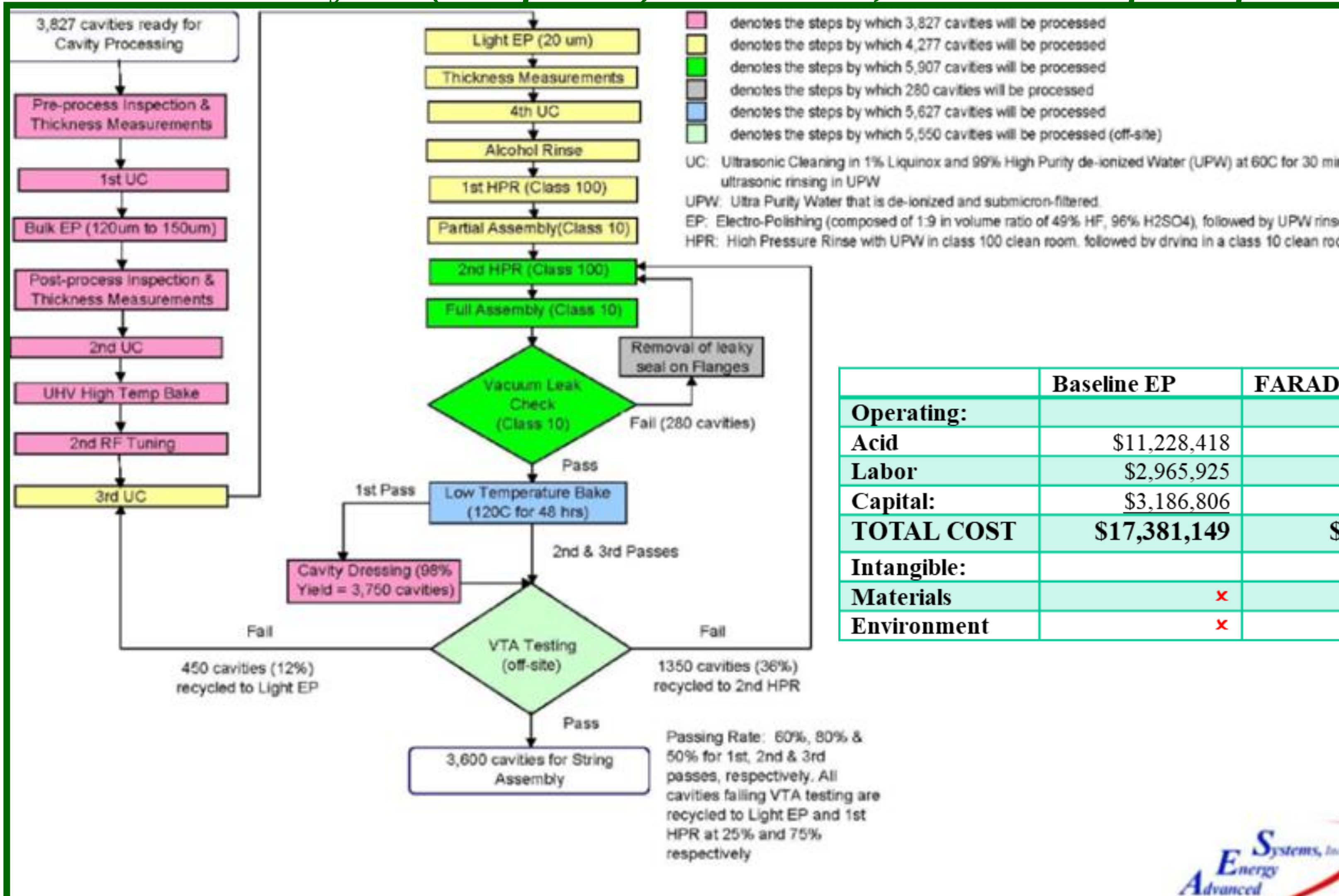
1) **Direct Sales to Accelerator Facilities:**
   a. R&D and service revenues;
   b. Apparatus design and fabrication revenues (e.g. ORNL $85,000 P.O.);
   c. Commission revenues on rectifier sales (dependent on advances related to "home-grown" rectifier at TJNAF).
2) **Licensee Revenues from Metal Finishing Industry:** (geography; Japan and Europe)
   a. Jump start license revenues for exclusive time-limited use;
   b. Industry wide non-exclusive license revenues;
   c. Commission revenues on rectifier sales (dependent on advances related to "home-grown" rectifier at TJNAF).
3) **EP Services for U.S. Cavity Production**
   a. As demand grows, co-license
      i. TechMetals, ABLE EP
   b. Cross-license TJNAF rectifier patent

JLAB: 1st β-Validation of FARADAYIC® HF-FREE EP
JLAB: Define *"Build to Print & Process"*

D. Sutter, B. Strauss "Technology Transfer – When, Why, Issues and Advantages" Proc. PAC07, MOZAC01 Albuquerque, NM 2007.

Commercialization: Economics

3,827 cavities over six years (U.S. portion) to meet the 3,600 cavities required for the ILC



	Baseline EP	FARADAYIC EP
Operating:		
Acid	$11,228,418	$1,125,138
Labor	$2,965,925	$1,817,825
Capital:	$3,186,806	$1,712,647
TOTAL COST	**$17,381,149**	**$4,655,610**
Intangible:		
Materials	✗	✓
Environment	✗	✓

E.J. Taylor, M. Inman, T. Hall, S. Snyder, A. Rowe, D. Holmes "Economics of Elecctropolishing Niobium SRF cavities in Eco-Friendly Aqueous Electrolytes without Hydrofluoric Acid" Proceedings of SRF2015 MOPB092 pp. 1-5 Whistler, CANADA (2015).

Industrialization: Post-Phase II Work

- High rate NO-ACID process (vis-à-vis 5% H_2SO_4)
  - Higher throughput ➔ less systems for given demand: CapEx
- Apparatus/cell design for industrialization
  - Racking/fixturing for metal finishing industry: Compatibility
- Waste recycle, recovery and disposal
  - Protocol for metal finishing industry: Compatibility
- Scale-Up of low cost rectifier breadboard (TJNAF; L. Phillips, C. Reece pat. Appl.)
  - ~$10K versus $80K used in AES economic study: CapEx/Strategic
- Waveform optimization
  - Higher throughput ➔ less systems for given demand: CapEx
- COMSOL modeling (confirming experiments) impact of electrode shape/shielding on current distribution, including “Ninja Electrode (Marui)
  - Improved material removal uniformity: OpEx/Strategic
- COMSOL modeling (confirming experiments) impact of electrode shape on electrolyte distribution, including “Ninja Electrode” (Marui)
  - Improved material removal uniformity: OpEx/Strategic
- Synergies with emerging cavity processing, cooling jackets (Mitsubishi)
  - Improved material removal uniformity: OpEx/Strategic

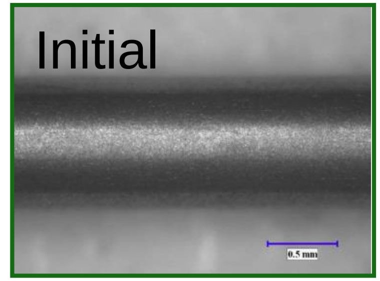
➔ β-scale testing; TJNAF, ORNL, FNAF, TechMetals, ABLE, KEK, Marui, Mitsubishi, Zannon, Research Instruments ➔ “Build to Print & Process”

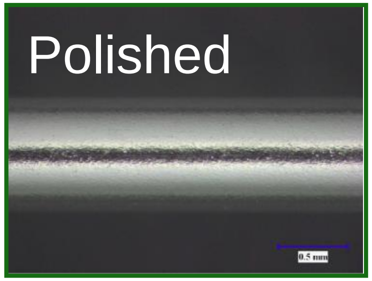
FARADAY TECHNOLOGY, INC.

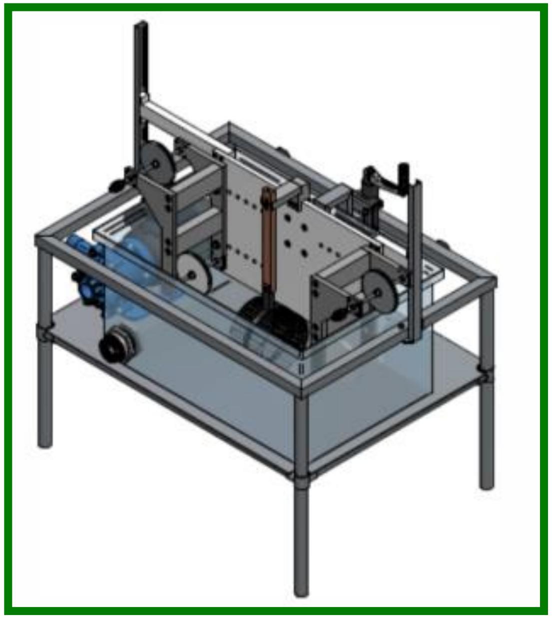
Commercialization: Spin-off

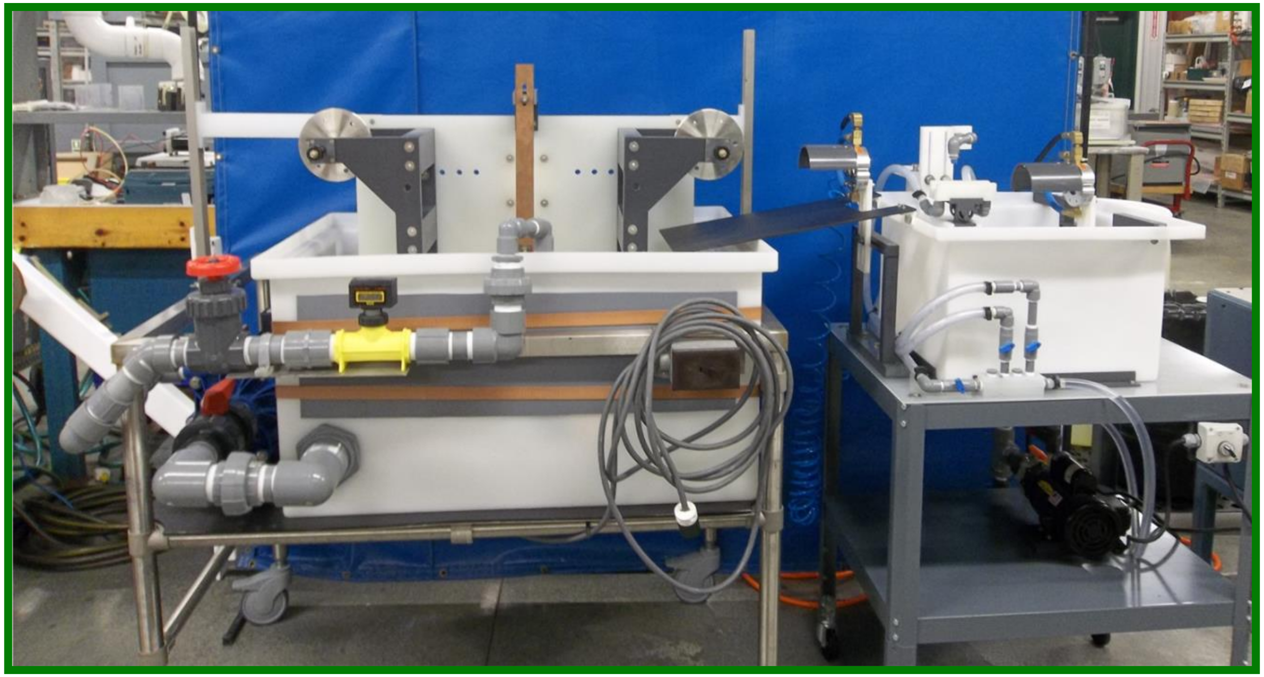
FARADAYIC® ElectroPolishing of Nitinol medical stents (similarities to Nb)

- Received Phase I & II funding from NIH ➔ process validation
- Project funding from OEM for adaptation to wire
  - α-scale reel-to-reel 300 foot spool trials
  - "toll" work >200 miles at Faraday
- LICENSED 4-12-2016









Acknowledgement

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1) SBIR Phase I Grant No. DE-SC0004588 (Dr. Manouchehr Farkhondeh),
2) SBIR Phase I Grant No. DE-FG02-08ER85053 (Dr. L.K. Ken),
3) American Reinvestment in Research Act (ARRA) (Mr. Allan Rowe, Fermi National Accelerator Laboratory),
4) SBIR Phase I/II Grant No. DE-SC0011235 (Dr. Manouchehr Farkhondeh),
5) SBIR Phase I/II Grant No. DE-SC0011342 (Dr. Kenneth R. Marken, Jr.).

Collaborators:

1) Dr. Fumio Furuta and Dr. Geoff Hoffstaetter; Cornell University
2) Dr. Hui Tian, Dr. Charles Reece and Dr. Larry Phillips; Jefferson Lab
3) Dr. John Mammosser and Dr. Jeff Saunders; Oak Ridge National Laboratory
4) Dr. Takayuki Saeki; KEK High Energy Accelerator Research Organization
5) Mr. Allan Rowe and Dr. Anna Grassellino; Fermi Laboratory

Technical Papers, Presentations and Patents

1) M. Inman, T. Hall, E.J. Taylor, C.E. Reece, O. Trofimova “Niobium Electropolishing in Aqueous, Non-viscous, HF-FREE Electrolyte: A New Polishing Mechanism” Proceedings of SRF2011 TUPO012 pp. 277-381 Chicago, IL (2011).
2) E.J. Taylor, M.E. Inman, T. D. Hall “Electrochemical System and Method for Electropolishing Superconductive Radio Frequency Cavities” U.S. Patent No. 9,006,147 filed July 11, 2012 issued April 14, 2015. (Foreign counterparts pending)
3) M. Inman, E.J. Taylor T.D. Hall “Electropolishing of Passive Materials in HF-Free Low Viscosity Aqueous Electrolytes” J. Electrochemical Society 160 (9) E94-E98 (2013).
4) A.M. Rowe, A. Grassellino, T.D. Hall, M.E. Inman, S.T. Snyder, E.J. Taylor “Bipolar EP: Electropolishing without Fluorine in a Water Based Electrolyte” Proceedings of SRF2013 TUIOC02 pp. 401-406 Paris, FRANCE (2013).
5) E.J. Taylor, M. Inman “Electrochemical Surface Finishing” *Interface* 23(3) pp. 57-61 Fall 2014.
6) E.J. Taylor, T. Hall, M. Inman, S. Snyder, A. Rowe “Elecctropolishing of Niobium SRF Cavities in Low Viscosity Aqueous Electrolytes without Hydrofluoric Acid” Proceedings of SRF2013 TUP054 pp. 534-7 Paris, FRANCE (2015).
7) E.J. Taylor, T.D. Hall, S. Snyder, M.E. Inman “Electropolishing of Niobium SRF Cavities in Low-Viscosirt, Water-Based, HF-Free Electrolyte: From Coupons to Cavities” Invited Talk 226th Meeting of the Electrochemical Society and XIX Congreso de la Sociedad Mexicana de Electroquimica, MEXICO (2014)
8) E.J. Taylor, M.E. Inman, T. D. Hall “Electrochemical System and Method for Electropolishing Superconductive Radio Frequency Cavities” U.S. Patent Appl. No. 14/585,897 filed December 30, 2014.
9) E.J. Taylor, M. Inman, T. Hall, S. Snyder, A. Rowe, D. Holmes “Economics of Elecctropolishing Niobium SRF cavities in Eco-Friendly Aqueous Electrolytes without Hydrofluoric Acid” Proceedings of SRF2015 MOPB092 pp. 1-5 Whistler, CANADA (2015).
10) E.J. Taylor, M. Inman “Vertical Eecctropolishing Studies at Cornell” Proceedings of SRF2015 MOPB093 pp. 364-7, Whistler, CANADA (2015).
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12) E.J. Taylor, M.E. Inman, H.M. Garich, H.A. McCrabb, S.T. Snyder, T.D. Hall “Breaking the Chemical Paradigm in Electrochemical Engineering: Case Studies and Lessons Learned from Plating to Polishing” in *Advances in Electrochemical Science and Engineering* Vol 18 R.C. Alkire (ed) Wiley-VCH scheduled Fall (2018).

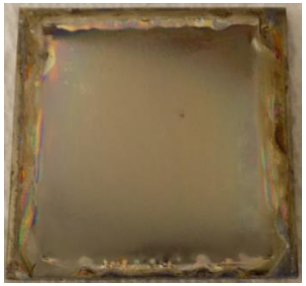
SUPPLEMENTAL SLIDES

Acid-Free EP

FARADAY TECHNOLOGY, INC.

Coupon Study

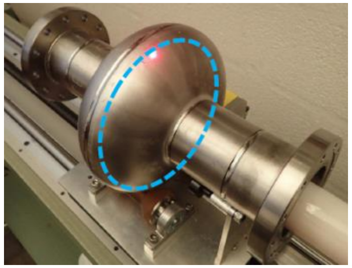
- $NaNO_3$ based electrolyte (pH 7.5)
- A:C area ratio = 1:0.4 (at ~1 ½” gap) and 1:0.2 (at ~3” gap)
- No change in pH or DSA tool fouling was observed
- Achieved an Ra of 0.27 µm in both beam tube and equator simulated coupon studies

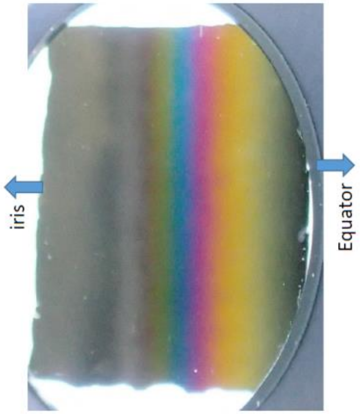


Initial R_a = 0.70 µm
Final R_a = 0.27 µm
Removal rate = 1.33 µm/h

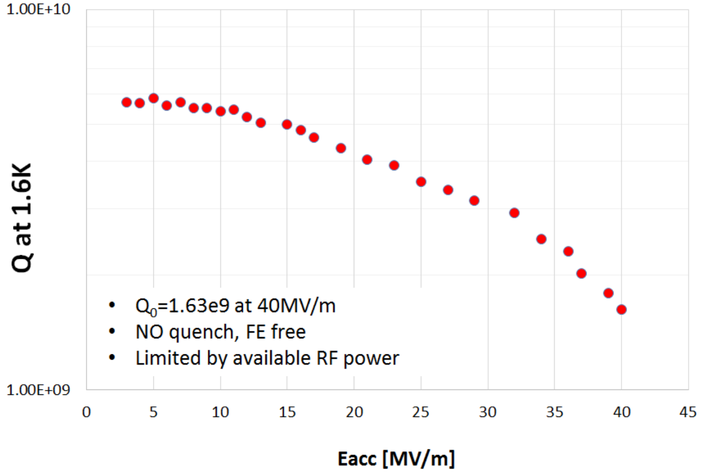
Single Cell SRF Cavity Polishing with $NaNO_3$ Acid-Free Electrolyte

~28.8 µm removed
1.60 µm/h

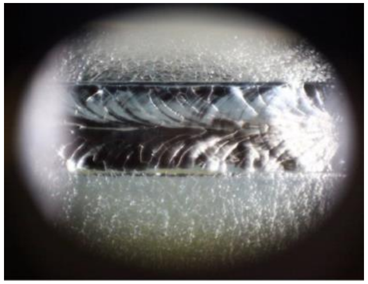




Coloration observed in between equator and beam tube distance while processing cavity

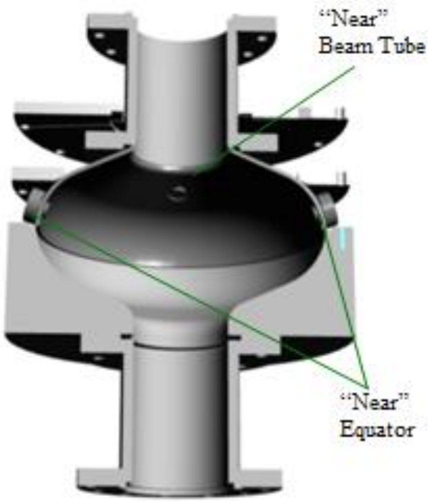


Q vs Eacc meas. was performed at 1.6K due to the low Q.



Cavity Equator

Button-Cell Half SRF Cavity Studies



Button Near Iris

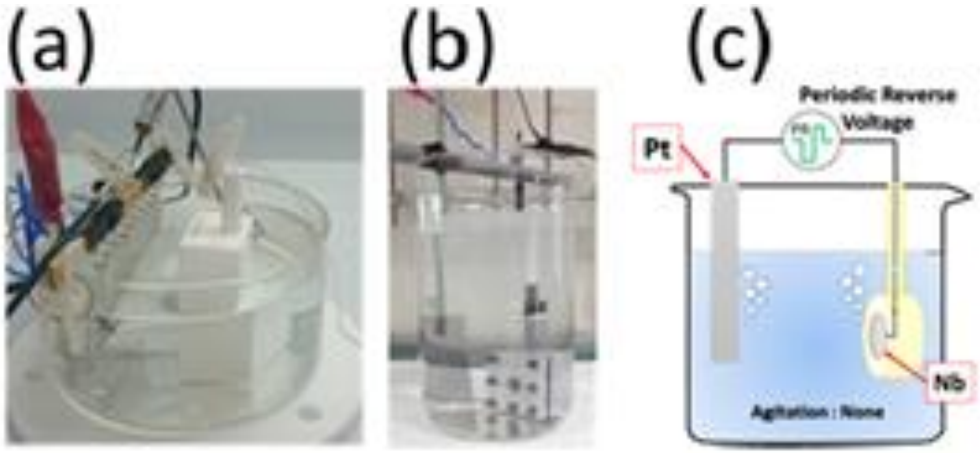
Button Equator

Coloration was also observed on Nb button study in similar position as single cell cavity

Acid-Free EP – TJNAF, Nomura

NaOH and $(COOH)_2$ based solution

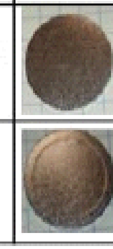
Experimental Setup



(a) A setup at Jefferson Laboratory, (b) a setup at Nomura Plating Co., Ltd, and (c) schematic illustration of setup

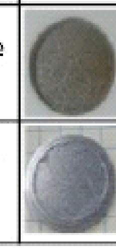
Parameter set No.		1	2	3	4	5	6
Solution		H_2SO_4 37%	NaOH 30% $(COOH)_2$ 0.05%	H_2SO_4 50%	NaOH 10% $(COOH)_2$ 0.05%	NaOH 10% $(COOH)_2$ 0.05%	NaOH 10% $(COOH)_2$ 0.05%
Temperature		20	50	20	20	50	50
PR wave form positive pulse	Voltage [V]	3					
	Pulse width [ms]	2.5	2.5	3	3	3	3
	Turn off time [ms]	1	0	0	0	0	5
PR wave form negative pulse	Voltage [V]	9					
	Pulse width [ms]	2.5	2.5	3	3	3	3
	Turn off time [ms]	0	5	5	5	5	5

	picture	Roughness (Ry) [um]
Before EP		NA
After EP		NA



(a) Parameter set No. 1

	picture	Roughness (Ry) [um]
Before EP		NA
After EP		NA

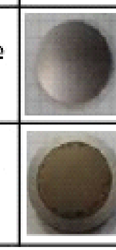


(b) Parameter set No. 2

	picture	Roughness (Ry) [um]
Before EP		3.8
After EP		5.4

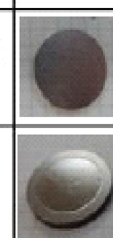
(c) Parameter set No. 3

	picture	Roughness (Ry) [um]
Before EP		3.5
After EP		2.0



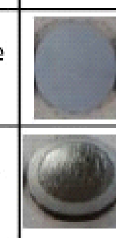
(d) Parameter set No. 4

	picture	Roughness (Ry) [um]
Before EP		5.1
After EP		2.5



(e) Parameter set No. 5

	picture	Roughness (Ry) [um]
Before EP		3.8
After EP		1.6



(f) Parameter set No. 6

Junji Taguchi, Akihiro Namekawa, Nomura plating Co., Ltd, Nishiyodogawa, Osaka Japan, Charles E. Reece, Hui Tian, Jefferson laboratry, Newport News, Virginia USA, Hitoshi Hayano, Takayuki Saeki†, KEK / Soukendai, Tukuba, Ibaraki Japan, "Study on electro-polishing of nb surface by periodic reverse current method with sodium hydroxide solution**", Proceedings of IPAC2016, Busan, Korea*

Representative Gap & Area Ratios

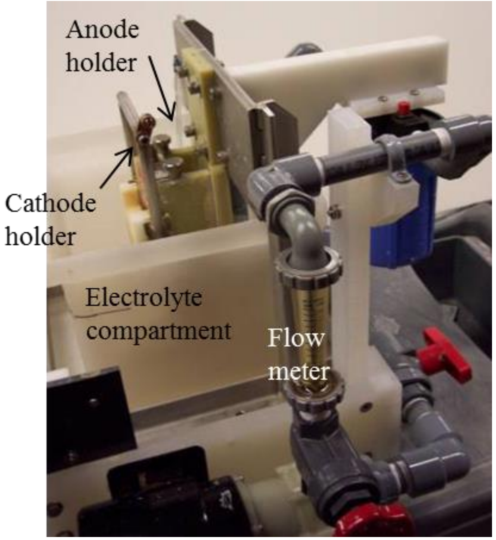
In 10% NaOH and 0.05% $(COOH)_2$

Factors explored:

1. A:C area ratio = 1:0.4 and 1:0.2
2. Anode to Cathode Distance (Beam Tube and Equator)

Observations

- Increased Ra to 1.07 µm from 0.79 µm



ElectroCell used at Faraday

After Processing (NaOH based solution)

Beam Tube
(Distance and Area Ratio)
Final Ra = 1.07 µm

Equator
(Distance and Area Ratio)
Final Ra = 1.35 µm

After Processing ($NaNO_3$ based solution)

Faraday (Equator and Beam Tube)
Final Ra = 0.27 µm

Vision: Pulse Current/Pulse Reverse Current

"…to be known as the company that changed the focus of electrochemical engineering from the art of complex chemistries to the science of pulse/pulse reverse electric fields…"

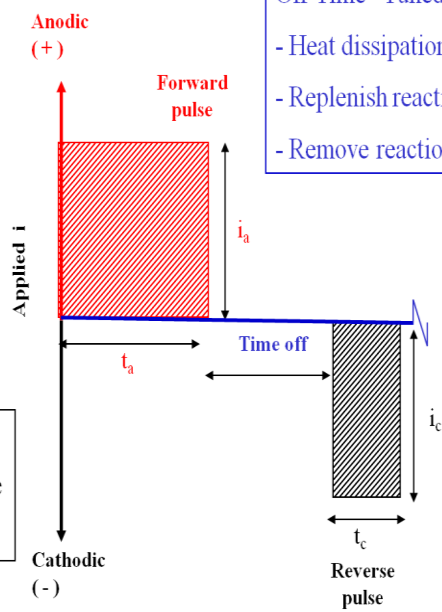
Electrochemical Machining, Polishing, Deburring, Through-Mask_Etching

Anodic Pulse "Tuned" to:

- Control current distribution
  → Eliminates need for viscous, low water content electrolytes

Off-Time "Tuned" to:

- Heat dissipation
- Replenish reacting species
- Remove reaction products



Cathodic Pulse "Tuned" to:

- Reduce oxide/depassivate surface
  → Eliminate need for HF

- 2008 Blum Award for Pulse Reverse Finishing
- 2016 R&D 100 Finalist for Nb EP

Electrodeposition/Plating

Cathodic Pulse "Tuned" to:

- Enhance mass transfer
- Control current distribution

→ Simplify chemistry

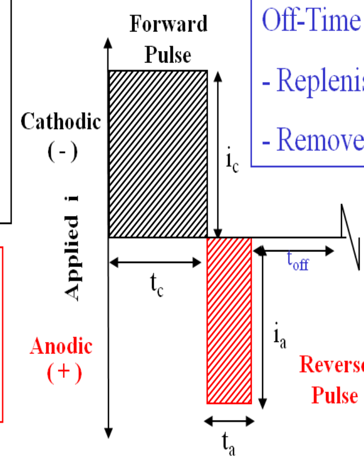
Anodic Pulse "Tuned" to:

- Remove H_2 effects

→ Acidify interface

Off-Time "Tuned" to:

- Replenish reacting species
- Remove reaction products



- 2011 R&D 100 for Co-Mn Alloy Plating
- 2013 Presidential Green Chemistry Challenge award for Cr^{+3} Plating

FARADAY TECHNOLOGY, INC.

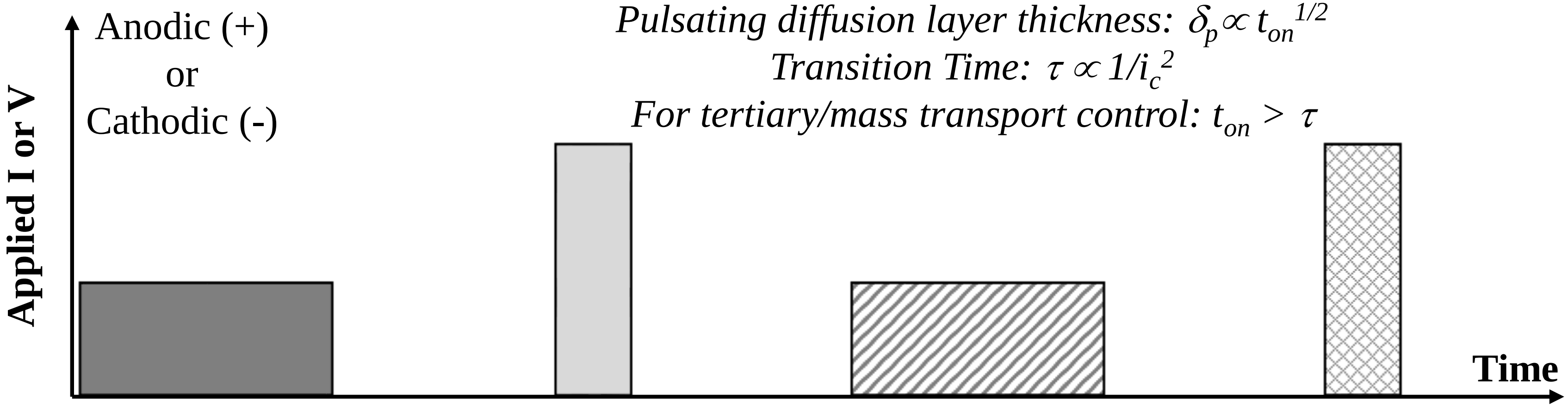
Guidance for Pulse Waveform Parameters

KEY RELATIONSHIPS

Pulsating diffusion layer thickness: $\delta_p \propto t_{on}^{1/2}$

Transition Time: $\tau \propto 1/i_c^2$

For tertiary/mass transport control: $t_{on} > \tau$



MACROPROFILE	MACROPROFILE	MICROPROFILE	MICROPROFILE
Long $t_{on} \rightarrow \delta_p < \delta$	Short $t_{on} \rightarrow \delta_p << \delta$	Long $t_{on} \rightarrow \delta_p < \delta$	Short $t_{on} \rightarrow \delta_p << \delta$
Larger pulsating diffusion layer maintains macroprofile	Smaller pulsating diffusion layer maintains macroprofile	Larger pulsating diffusion layer maintains microprofile	Smaller pulsating diffusion layer converts microprofile to macroprofile
Low $i_{peak} \rightarrow$ Higher τ Design $t_{on} >> \tau$	High $i_{peak} \rightarrow$ Smaller τ Design $t_{on} << \tau$	Low $i_{peak} \rightarrow$ Higher τ Design $t_{on} >> \tau$	High $i_{peak} \rightarrow$ Smaller τ Design $t_{on} >> \tau$
Favors more tertiary control	Favors more primary or secondary control	Favors more tertiary control	Favors more tertiary control
SLIGHTLY MORE **NON-UNIFORM** THAN DC	*SIGNIFICANTLY MORE* **NON-UNIFORM** THAN DC	*SLIGHTLY MORE* **UNIFORM** THAN DC	*SIGNIFICANTLY MORE* **UNIFORM** THAN DC

Adv in Electrochemical Science and Engineering XVIII: "Breaking the Chemical Paradigm in Electrochemical Engineering: Case Studies and Lessons Learning from Plating to Polishing" publication scheduled Fall 2018.

Commercialization: Synergistic IP?

US009674936B2

(12) **United States Patent**
Hara

(10) **Patent No.: US 9,674,936 B2**
(45) **Date of Patent: Jun. 6, 2017**

(54) **SUPERCONDUCTING ACCELERATING CAVITY AND ELECTROPOLISHING METHOD FOR SUPERCONDUCTING ACCELERATING CAVITY**

(71) Applicant: **MITSUBISHI HEAVY INDUSTRIES, LTD.**, Tokyo (JP)

(72) Inventor: **Hiroshi Hara**, Tokyo (JP)

(73) Assignee: **MITSUBISHI HEAVY INDUSTRIES MECHATRONICS SYSTEMS, LTD.**, Hyogo (JP)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 315 days.

(21) Appl. No.: **14/494,867**

(22) Filed: **Sep. 24, 2014**

(65) **Prior Publication Data**

US 2015/0163894 A1 Jun. 11, 2015

(30) **Foreign Application Priority Data**

Dec. 5, 2013 (JP) 2013-252262

(51) **Int. Cl.**
H05H 7/20 (2006.01)
C25F 3/26 (2006.01)

(52) **U.S. Cl.**
CPC ***H05H 7/20*** (2013.01); ***C25F 3/26*** (2013.01)

(58) **Field of Classification Search**
CPC H05H 15/00; H05H 7/20
See application file for complete search history.

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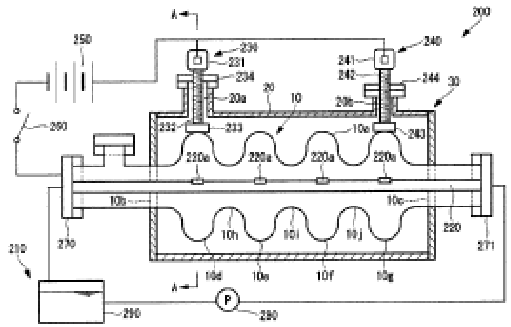
(Continued)

Primary Examiner — Nicholas A Smith
(74) *Attorney, Agent, or Firm* — Wenderoth, Lind & Ponack, L.L.P.

(57) **ABSTRACT**

Provided is a superconducting accelerating cavity **30** including: a cavity main body **10** formed of a superconducting material into a cylindrical shape; and a refrigerant tank **20** installed around the cavity main body **10** and storing a refrigerant which is supplied from the outside through a supply port **20a** into a space formed between the refrigerant tank and the outer circumferential surface of the cavity main body **10**, wherein the outer circumferential surface of the cavity main body **10** is coated with a metal coating layer **10a** having a higher conductivity than the superconducting material.

7 Claims, 7 Drawing Sheets



Superconducting Accelerating Cavity and Electropolishing Method for Superconducting Accelerating Cavity

Assignee: Mitsubishi Heavy Industries LTD

- Cooling jacket for temperature control during EP
- Directed towards current high viscosity H_2SO_4 / HF solution

➔ May be beneficial with FARADAYIC® HF-FREE EP?

FARADAY TECHNOLOGY, INC.

Commercialization: Synergistic IP?

US009689086B2

(12) **United States Patent**
Ida

(10) **Patent No.: US 9,689,086 B2**
(45) **Date of Patent: Jun. 27, 2017**

(54) **ELECTRODE FOR POLISHING HOLLOW TUBE, AND ELECTROLYTIC POLISHING METHOD USING SAME**

(71) Applicant: **MARUI GALVANIZING CO., LTD.**, Hyogo (JP)

(72) Inventor: **Yoshiaki Ida**, Hyogo (JP)

(73) Assignee: **MARUI GALVANIZING CO., LTD.**, Hyogo (JP)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 395 days.

(21) Appl. No.: **14/413,520**

(22) PCT Filed: **Jul. 8, 2013**

(86) PCT No.: **PCT/JP2013/068593**
§ 371 (c)(1),
(2) Date: **Jan. 8, 2015**

(87) PCT Pub. No.: **WO2014/010540**
PCT Pub. Date: **Jan. 16, 2014**

(65) **Prior Publication Data**
US 2015/0159294 A1 Jun. 11, 2015

(30) **Foreign Application Priority Data**
Jul. 11, 2012 (JP) 2012-155490

(51) **Int. Cl.**
C25F 7/00 (2006.01)
C25F 3/16 (2006.01)
C25F 7/02 (2006.01)

(52) **U.S. Cl.**
CPC *C25F 7/00* (2013.01); *C25F 3/16* (2013.01); *C25F 7/02* (2013.01)

(58) **Field of Classification Search**
CPC C25F 3/16; C25F 7/00
See application file for complete search history.

(56) **References Cited**

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(Continued)

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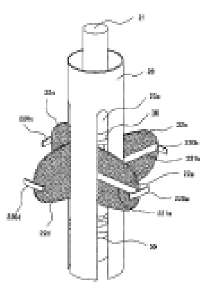
(Continued)

Primary Examiner — Nicholas A Smith
(74) *Attorney, Agent, or Firm* — Wenderoth, Lind & Ponack, L.L.P.

(57) **ABSTRACT**

A wing electrode is configured by disposing at least a wing in a circumferential direction at equal intervals, the wing having a specific width in an axial direction of the electrode shaft and a tip in a shape corresponding to an inner surface of the hollow tube. A housing tube is arranged concentrically to the electrode shaft and to house the wing electrode by winding the respective wings around the electrode shaft. A slit of the housing tube is arranged in the axial direction so as to correspond to each wing. A diameter adjustment unit is operable to expand and contract each wing in the radial direction by rotating the electrode shaft and the housing tube relatively after inserting each wing into the slit of the housing tube. As a matter of course, the electrolyte is filled in the hollow tube at any time before the electrolytic treatment.

5 Claims, 13 Drawing Sheets



Electrode for Polishing Hollow Tube and Electrolytic Polishing Method using Same

Assignee: Marui Galvanizing Co, LTD

- Electrode "protrusions" for promoting
  - Improved mixing,
  - Improved current uniformity
- Directed towards current high viscosity H_2SO_4 / HF solution

➔ May be beneficial with FARADAYIC® HF-FREE EP?