FNAL 3-year Single-Cell SRF Cavity Program

- Timeframe: the 3-year period starting mid-FY2009 (3/1/09) through mid-FY2012 (2/29/12)
- Objectives:
  - Carry forward the single-cell S0 program (incremental improvement, *concepts directly transferrable to projects*)
  - Initiate a coordinated program to address generic topics for SRF, in particular the development of an understanding of performance limits on the basis of materials and processing (*transformational improvement*, designs or processes that could deviate largely from existing baselines)
  - Use single-cell projects to fill personnel pipelines and encourage learning at industry, labs, and academia.

What might we obtain if the program succeeds?

- EP processes tuned to in-line fluorine monitors, oxidation kinetics, and material texture
- Tumbling and chemical-mechanical polishing recipes
- Improved material specifications
- Pit-free welded cavities
- In-process remediation strategies for various performance limitations
- Feasibility of niobium-on-copper cavities by new routes
- Hydroformed single-cell cavities
- Cavities beyond the limit of niobium

Definitions

Baseline *Single-Cell* Processing Recipe

1. Incoming cavity quality control checks.
2. *Optical inspection of as-received cavity.*
3. Bulk electro-polishing of ~150 um.
4. Ultrasonic degreasing.
5. High-pressure rinsing.
6. Hydrogen degassing at 600-800 °C.
7. *Optical inspection.*
8. 20 μm electro-polishing.
9. Ultrasonic degreasing.
10. High-pressure rinsing.
11. Assembly and vacuum leak testing.
12. 120 °C bake.
13. Vertical test.

Standard Testing Recipe

1. Hold at ~100 K during cool down to check for Q disease.
2. Q vs. T during cool down.
3. Q vs. E. RF process as needed.
4. Final Q vs. E measurement.

Diagnostic Techniques

1. Apply thermometry to determine location of limiting defect.
2. Perform optical inspection.
3. *Remediate defect, rinse/proces, retest.*

Performance Standards

1. "Qualified": **30** MV/m after being given the baseline process above.
2. *OR* 25 MV/m after an alternate process where BCP is substituted for EP in the baseline above and no final etching (steps 7-10).

Scientific Approach

1. Qualify new vendors of SRF cavities
2. Proof-of-concept experiments to test process improvements
3. Supply reference cavities for qualification of tools, procedures, processes, test stands, equipment…
4. Collaborate
   a) Supply benchmark cavities to serve as a baseline for subsequent experiments done by collaborators.
   b) Receive, process, and test cavities from collaborators
5. Test new cavity ideas
6. Develop characterization tools

Work Breakdown

Work Area		FY09-FY10	FY10-FY11	FY11-FY12	Total
1 – Qualify Vendors	# of EP		9		9
	# of test cycles		9		9
2 – Proof-of-concept	# of EP	12	12	3	27
	# of test cycles	14	12	3	29
3 – Reference cavities	# of EP	0	6		6
	# of test cycles	6	6		12
4a – Benchmarks for collaborators	# of EP	2	2	0	4
	# of test cycles	12	4	10	26
4b – Process/test requests from collaborators	# of EP		10	4	14
	# of test cycles		11	4	15
5 – New Ideas	# of EP	10	10		20
	# of test cycles	17	10		27
6 – Characterization	# of EP	0			0
	# of test cycles	0			0
Total EP		**24***	**49**	**7**	**80**
Total VTS		**49**	**52**	**17**	**118**

** Some cavities in inventory are already qualified*

Work details - 1. Qualify Vendors

- PAVAC: Anticipated purchase of ~6 cavities late FY09 to early FY10.
- HC Starck sheets: Fabricate 2-6 cavities using sheets from this new vendor. The manufacturer is to be determined.

Work details - 2. Proof-of-concept

- Tumbling (FNAL):
  - Develop a tumbling regimen (e.g. 150 μm removal by tumbling + 20 μm by final EP)
  - Tumble ~2 qualified and ~2 unqualified cavities
  - Compare results for tumbling to baseline EP process
  - Compare whether tumbling improves or degrades process.
- ECS validation (FNAL)
  - Fabricate 2 cavities with known ECS defects (done)
  - Evaluate performance for baseline process
  - Compare with coupon studies
- High fluorine concentration processing (FNAL + JLab):
  - "Flash" process ~4 cavities, compare to baseline
  - Develop in-situ fluorine monitor (purchase Raman spectrometer?)
  - Process coupons in parallel
- Large grain
  - Fabricate ~2 large grain cavities with Niowave
  - Apply baseline and non-baseline processes
  - Evaluate cost claims

Work details - 3. Reference cavities
6. Develop characterization tools

- Complete full qualification of ANL facility with single cell cavities
- A0 test facility
  - Qualify with known low, medium, and high-gradient single-cell cavities.
- ICPA
  - Expect certification mid FY10.
  - Qualify facility with ~6 EP cycles on previously qualified cavities.
  - Attain qualifying gradient 3 consecutive times
- IB4 Oven:
  - Qualify after planned upgrade (FY2010 or later)
- High-resolution Tmap systems (FNAL, JLab, Cornell):
  - Set aside cavities with known defects and well-researched behavior
  - Develop standard reference cavities
- Optical inspection:
  - Develop standard reference cavities with hand-made pits
  - Apply calibration markings

Work details - 4a. Benchmarks to collaborators

- Atomic Layer Deposition
  - Cap and Bake (ANL and JLab): 1-2 cavities, covered with alumina and baked to solvate oxide, then test
  - Niobium on Niobium (ANL): 1 cavity for experiments after PEALD is developed (FY10)
  - Multilayer (ANL): After demonstration of Nb on Nb, 1 cavity will be used for Nb / alumina multilayer (FY11)
  - Niobium on Copper: After PEALD, coat 1-2 copper cavities from India (FY11)
- MgB_2 (Penn State)
  - Qualified 3.9 GHz cavity already ear-marked for coating with MgB_2
  - Pending funds, expect cavity for test FY10
- EP (Able)
  - Provide ~6 qualified cavities to evaluate industrial electropolishing.
  - HPR, assembly, and VTS at FNAL

Work details - 4a. Benchmarks to collaborators (cont.) 4b. Process / test requests from collaborators

- Chemical-mechanical polishing (CMP – Cabot and Northeastern)
  - Cabot: Provide ~3 qualified cavities for final CMP, VTS at Fermilab (FY09-10)
  - Cabot to FNAL: transfer of CMP slurries to Fermi tumbling program, ~3 cavities (FY11)
  - NE: ~2 new cavities to be made from polished sheets and polished ½ cells, then welded at AES (outside funds). VTS and possible re-process @ FNAL.
- Weld pre-conditioning (FNAL + Black Labs + vendor TBD):
  - Fabricate ~2 cavities with fully recrystallized half cells prior to welding
  - Fabricate ~2 cavities with recovered but not recrystallized half cells prior to welding
  - Apply baseline EP and evaluate performance
  - Search for pits and other defects
  - Use witness coupons in parallel

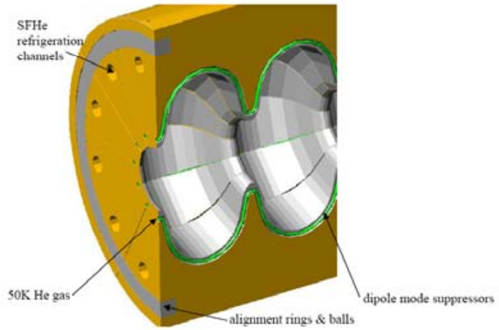
Work details – 4b. Process / test requests from collaborators (cont.)

- Hydroformed cavities (MSU, Ohio State, Texas A&M, Black Labs)
- MSU:
  - Complete 3.9 GHz copper (1 cavity) and niobium (1 cavity) hydroforming (FY09-10). Send to FNAL for test.
  - Produce hydroformed single-crystal 3.9 GHz cavity with Nevada-Reno and Wah Chang (FY10-11)
  - MSU / UNR: (if scale up $$) attempt single-crystal 1.3 GHz hydroformed cavity (FY11-12)
- Ohio State (with SBIR $$)
  - Expect to have extrusion-bonded Nb/Cu tubes FY10, will process @ OSU or DESY FY11 and send to FNAL for process / test.
- TAMU (+FNAL)
  - Process seamed tube, deliver to MSU for hydroforming, then to FNAL for process / test
- Black Labs (with SBIR $$)
  - Will be hydroforming flow-formed tubes at DESY FY09-10, then to FNAL for process / test

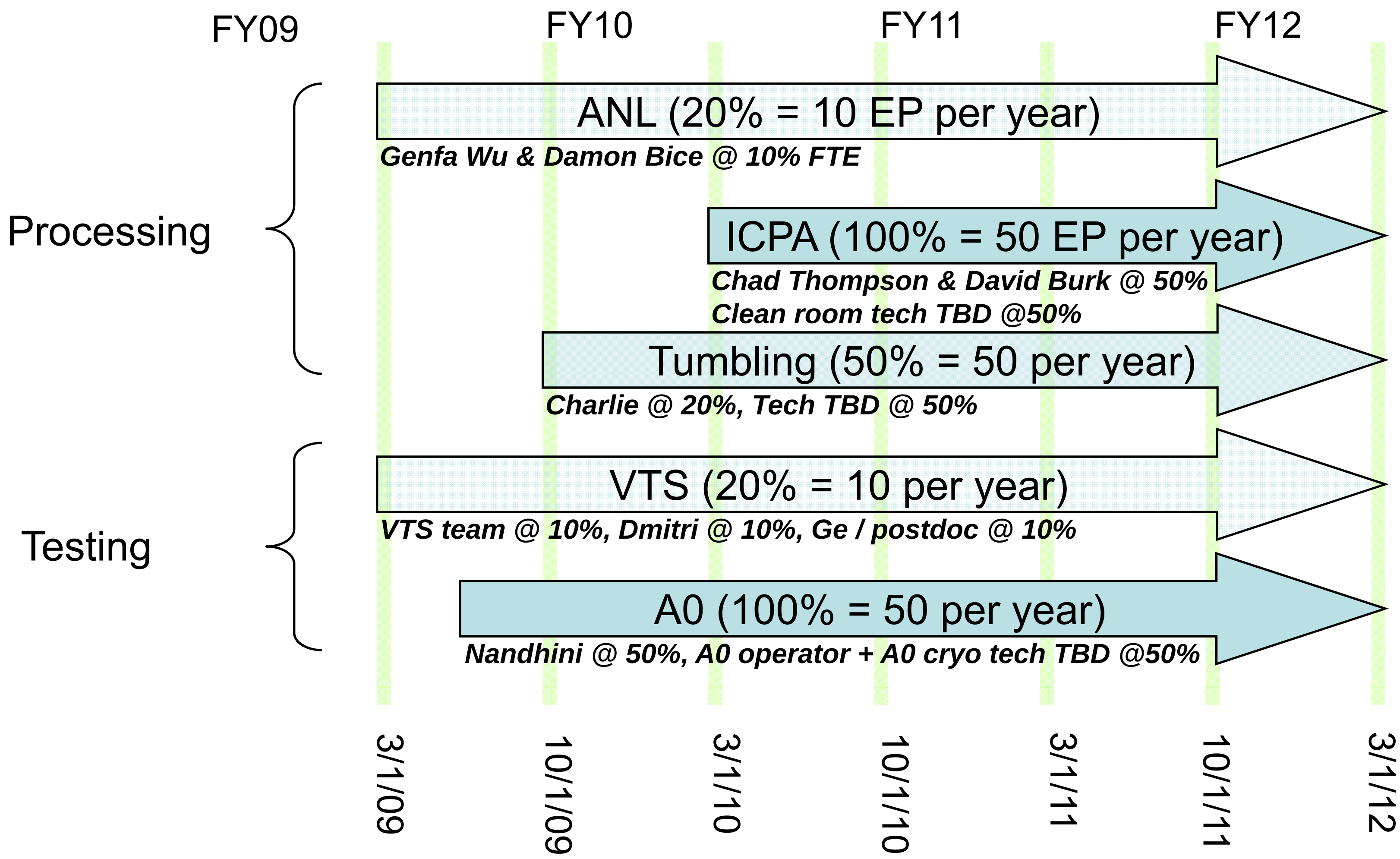
Work details - 5. New ideas

- In-situ remediation:
  - FY10: Complete several tests of laser re-melting in ~3 cavities.
  - Re-process / test as needed; Investigate post-melting processes – light EP + ultrasonic + HPR, or just ultrasonic + HPR.
  - FY11-12: Develop laser re-melting in-situ with optical inspection
- Plasma post-process: continue summer intern work, extend to 1.3 GHz

- “Quench” cavity:
  - FY10-FY11: Fabricate ~2 custom cavities with new shape …
  - … 1 from standard material and process, 1+ using materials and processing parameters that we suspect lead to defects
  - Evaluate usefulness
- Polyhedral cavity (with TAMU):



Processing and testing effort



Present cavity inventory

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3C1

3.9GHz Single Cell Summary 3C: 3rd harmonic single cell center cell   Last updated on 2/12/2009

Number	Current location	Main purpose	Current Status	Notes	Delivery date	Order Date
3C1FER001	FNAL_IB3	Tumble+EP		C Cooper	~2006	
3C1FER002	ABLE	Tumble+EP	EP setup	C Cooper	~2006	
3C1FER003	ICB first floor	GCIB, Plasma	Waiting for RF components	G Wu	~2006	
3C1ROA001	Reeves's office	Tumble+EP		C Cooper	9/15/2007	
3C1ROA002	Reeves's office	BCP verification			9/15/2007	
3C1ROA003	Reeves's office	ALD	To be degreased, queued after 3C1ROA005		9/15/2007	
3C1ROA004	FNAL_ICB	helium processing	BCP 80 minutes done, early quench	around 12 MV/m quenched	9/15/2007	
3C1ROA005	FNAL/MDTL	MgB2	80 min BCP done, waiting for funding	G Wu Shorter beam pipe	9/15/2007	
3C1FER004	A0 cabinet	Tumble+EP		C Cooper	3/7/2008	
3C1FER005	A0 cabinet	Tumble+EP		C Cooper	3/7/2008	
3C1FER006	A0 cabinet	ALD, Tumble+EP		NbTi material ready 8/9/2007	3/7/2008	
3C1FER007	A0 cabinet	Plasma processing		Uses 9-cell flange with transision rings	3/7/2008	
3C1FER008	To be made at Fermilab	Large grain study		Blanks ready to scan on 8/15/2007		
3C1FER009	To be made at Fermilab	Large grain study				
3C1FER010	To be made at Fermilab	Single crystal study				
3C1FER011	To be made at Fermilab	Single crystal study		Blanks ready		

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TE1

1.3GHz Single Cell Summary TE: Tesla Endcell shape

Number	Current location	Main purpose	Current status	Notes	Delivery date	Order Date
TE1AES001	JLAB	Single cell EP	At Jlab, single cell EP setup	27.8 MV/m limited by Q-slope	8/31/2007	6/11/2007
TE1AES002	Cornell Univ.	Q-slope	Medium field Q-slope	17 MV/m limited by FE	8/31/2007	6/11/2007
TE1AES003	TRIUMF	TRIUMF commissioning		28 MV/m limited by Q-slope	8/31/2007	6/11/2007
TE1AES004	FNAL IB1	Equator pit, quench at high	visual inspection done, HPR pit study	39.2 MV/m, limited by Quench	8/31/2007	6/11/2007
TE1AES005	ANL208	CMP studies, EP, ABLE	Seal surface scratches, repaired	26.7 MV/m limited by Q-slope	8/31/2007	6/11/2007
TE1AES006	Cornell Univ.	Q-slope	Medium field Q-slope	To be tested soon	8/31/2007	6/11/2007
TE1ACC001	FNAL ICB	EP Optimization	inspected and To be EP at ANL		12/29/2008	3/26/2008
TE1ACC002	ANL208	EP Optimization	112 micron EP, RF test done	33 MV/m limited by FE and Qslope	12/29/2008	3/26/2008
TE1ACC003	FNAL ICB	EP Optimization	To be inspected and EP		12/29/2008	3/26/2008
TE1ACC004	FNAL ICB	EP Optimization	To be inspected and EP		12/29/2008	3/26/2008
TE1ACC005	FNAL ICB	Eddy current scanning	To be inspected and progressive EP		12/29/2008	3/26/2008
TE1ACC006	FNAL ICB	Eddy current scanning	To be inspected and progressive EP		12/29/2008	3/26/2008
NR-1	Cornell Univ.		in transit to Cornell	26.5 MV/m limited by FE, Quench	6/11/2008	
NR-2	Cornell Univ.		VEP at Cornell	26 MV/m limited by Quench after VEP	6/11/2008	
NR-3	Cornell Univ.		More BCP done at Cornell	22.8 MV/m : new test result	6/11/2008	
NR-4	FNAL/A0	ABLE EP	Connected to vacuum pump	28.7 MV/m limited by Q-slope	6/11/2008	
NR-5	Cornell Univ.	E-beam weld on Pit	equator weld pit	24.7 MV/m limited by Quench	6/11/2008	
NR-6	Cornell Univ.	Laser re-melting	equator weld pit	26.8 MV/m limited by Quench	6/11/2008	
	NR single cell summary report by Cornell on 11/12/2008					

Start of a project plan

Appendix B - Breakdown of individual single-cell experiments

Work Area	Single-cell experiment	Work period	Duration (20d/mo)	# existing 3.9 GHz cavities	# existing 1.3 GHz cavities	# new 3.9	# new 1.3	Inventory assignment
1 - qualify vendors	Qualification of PAVAC cavities	FY10-FY11	120	0	0	0	6	NEW TE1PAV001-006
1 - qualify vendors	Qualification of HC Starck	FY10-FY11	60	0	0	0	3	NEW TE1STK001-003
2 - proof-of-concept	Tumbling experiments	FY09-FY10	200	3	4	0	0	3C1ROA001, 3C1FER004 and 005; 1.3 GHz cavities to be assigned
2 - proof-of-concept	ECS defect	FY09-FY10	80	0	2	0	0	TE1ACC005 and 006
2 - proof-of-concept	High fluorine gradient	FY10-FY11	160	0	4	0	0	TE1AES001; 3 more required
2 - proof-of-concept	Weld pit studies	FY10-FY11	80	0	0	0	4	anticipated cavities made under atypical conditions
2 - proof-of-concept	Large grain	FY11-FY12	60	0	0	0	3	NEW Roark-Niowave from large grain
3 - reference	ANL Qualification	FY09-FY10	0	4	0	0	0	TE1ACC001-004
3 - reference	A0 VTS qualification	FY09-FY10	60	0	3	0	0	TBD
3 - reference	Tmap system development	FY09-FY10	60	0	1	0	0	cavity with known pit, e.g. NR5
3 - reference	ICPA certification	FY10-FY11	120	0	3	0	0	TE1ACC001-003 after completion of ANL qualification
4a - benchmarks to collaborators	ANL ALD cap and bake	FY09-FY10	80	2	0	0	0	3C1ROA003, 3C1FER006
4a - benchmarks to collaborators	ANL ALD niobium on niobium	FY11-FY12	40	1	1	0	0	will not start until PEALD is in place; can use ACC or NR cavity
4a - benchmarks to collaborators	ANL ALD multilayer	FY11-FY12	40	1	1	0	0	will not start until PEALD is in place; can use ACC or NR cavity

Start of a project plan

Appendix B - Breakdown of indi

Work Area	Single-cell experiment	Inventory assignment	# Baseline EP	# Other EP	Total EP	Other cycles	Notes	# of test cycles
1 - qualify vendors	Qualification of PAVAC cavities	NEW TE1PAV001-006	6	0	6			6
1 - qualify vendors	Qualification of HC Starck	NEW TE1STK001-003	3	0	3			3
2 - proof-of-concept	Tumbling experiments	3C1ROA001, 3C1FER004 and 005; 1.3 GHz cavities to be assigned	2	6	8	8	6 tumble + final EP, 2 baseline then test then tumble + final EP	10
2 - proof-of-concept	ECS defect	TE1ACC005 and 006	4	0	4			4
2 - proof-of-concept	High fluorine gradient	TE1AES001; 3 more required	4	4	8		2 baseline, 2 baseline + flash, 4 flash only - JLab?	8
2 - proof-of-concept	Weld pit studies	anticipated cavities made under atypical conditions	4	0	4			4
2 - proof-of-concept	Large grain	NEW Roark-Niowave from large grain	3	0	3			3
3 - reference	ANL Qualification	TE1ACC001-004	0	0	0		fully qualified at the start of this program	0
3 - reference	A0 VTS qualification	TBD	0	0	0			3
3 - reference	Tmap system development	cavity with known pit, e.g. NR5	0	0	0	3	3 cycles of modification of Tmap system	3
3 - reference	ICPA certification	TE1ACC001-003 after completion of ANL qualification	6	0	6			6
4a - benchmarks to collaborators	ANL ALD cap and bake	3C1ROA003, 3C1FER006	2	0	2			4
4a - benchmarks to collaborators	ANL ALD niobium on niobium	will not start until PEALD is in place; can use ACC or NR cavity	0	0	0	2	parameters loosely defined; anticipate 2 BCP	2
4a - benchmarks to collaborators	ANL ALD multilayer	will not start until PEALD is in place; can use ACC or NR cavity	0	0	0	2	parameters loosely defined; anticipate 2 BCP	2

Other development and equipment

- Need Tmap system for A0 (Muckerjee, 3 mo @ 50%)
- Need field emission detection for A0
- Will modify MDTL epoxy ovens for clean 120 °C bake (e.g. cavity in a bag with inert gas)
- Purchase or rebuild single-cell oven in IB4 for bake up to 1200 °C in high vacuum
- Purchase Raman spectrometer for in-situ fluorine ion monitoring
- Purchase additional optical inspection system
- Upgrade tumbling to accommodate slurries
- Support university and industry R&D programs

Budget

	FY09-FY10	FY10-FY11	FY11-FY12	
Total Sum of Total EP	24	49	7	80
Total Sum of # of test cycles	49	52	17	118

Cost item	Rate	FY09-FY10	FY10-FY11	FY11-FY12
Processing and testing				
EP + HPR costs	6000	144000	294000	42000
IB1 VTS	15000	120000	120000	120000
A0 VTS	8000	328000	352000	72000
Fixed costs				
IB4 clean room	18000	18000	18000	18000
A0 clean room	0	0	0	0
UHP water plant - IB4	10000	10000	10000	10000
UHP water plant - A0	0	0	0	0
ICPA (maint, clothes, etc)	8000	8000	8000	8000
ICPA completion	(under TD)			
Resource development				
A0 Tmap		50000		
Raman / FTIR (F- ion monitor)			175000	
Custom fabrication (2@8000)		16000	16000	16000
Tumbling upgrade for CMP				50000
New 1100 C oven			250000	
MDTL 120 C bake		15000		
Optical inspection standard		10000		
Optical inspection automation			40000	
Additional optical system				300000
Laser modifications for re-melting		10000		
Field emission monitoring @ A0		5000	5000	5000
Variable input couplers @ A0		10000		

Budget (cont.)

University programs				
MSU - testing and forming	already seeded	50000	50000	
MSU - textured sheet	seed-deliver-fabricate	30000	50000	50000
TAMU - tube forming	seed-deliver-fabricate	30000	80000	
OhSU - tube forming	possible HEP grant			
UNR - zone refining	upgrade	300000	30000	
Northeastern	possible NSF grant			
Penn State	possible HEP grant			
Industry programs				
CMP at Cabot, xfer to tumbler			50000	
Black Labs - hydroforming	DESY machine here?		20000	40000
Black Labs - Rx sheet	custom fab above			
ABLE EP	CRADA - separate??			
Starck - purchase	purchase-deliver	25000		
PAVAC - purchase	purchase-deliver	90000		
Total M&S		**1269000**	**1568000**	**731000**

$1M equipment

Budget (cont.)

Cost item	Rate	FY09-FY10	FY10-FY11	FY11-FY12
SWF	FTE			
Wu @ ANL	0.1	9000	9000	9000
Bice @ ANL	0.1	6000	6000	6000
Thompson @ ICPA	0.5	30000	30000	30000
Burk @ ICPA	0.5	22500	22500	22500
(TBD - clean rm) @ ICPA	0.5	22500	22500	22500
Dharanaj @ A0	0.5	45000	45000	45000
(TBD - VTS operator) @ A0	0.5	30000	30000	30000
(TBD - VTS cryo) @ A0	0.5	22500	22500	22500
(Muckerjee) - Tmap devel 3mo@0.5	0.13	11700	11700	11700
Inspection (Sergatskov or Ge)	0.2	18000	18000	18000
Tracking and logging (ND or MG)	0.2	18000	18000	18000
Weld metallurgist (Postdoc)	0.5	22500	22500	22500
Laser specialist (Wu, Nicol)	0.05	4500	4500	4500
Cooper - Tumbling @FNAL	0.2	18000	18000	18000
TBD - tech Tumbling @ FNAL	0.5	22500	22500	22500
Total SWF		**302700**	**302700**	**302700**
Program Total		**1571700**	**1870700**	**1033700**

Other issues

- A0 VTS — What is the future for this?
- ICPA: operational trials by mid FY2010 may be ambitious.

- Synergistic program in SRF Materials using coupons
- Synergistic university research programs FNAL+ANL+UC+IIT+NWU+FSU