

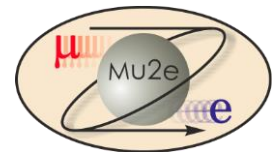


Solenoid Conductor Status

Vito Lombardo

DOE CD-2/3b Review

October 21-24, 2014



Outline

- Overview of the prototype phase
- Brief summary of production orders
 - Hitachi Cable:
 - Status of Transport Solenoid order
 - Status of Detector Solenoid 2 order
 - Furukawa Electric:
 - Status of Detector Solenoid 1 order
 - Status of Production Solenoid order
- Conclusions

Overview of Prototype Phase

- All four SC cables went through a successful prototype stage aimed at demonstrating the feasibility of such cables in industry.
 - About 3,600m of mu2e cables were successfully procured as part of this prototype campaign.
 - The orders were awarded to two vendors according to the following summary
- **Transport Solenoid: (3x1000m)**
 - Superconducting Wire (Hitachi, Japan) – **Completed**
 - Rutherford Cable (New England, US) – **Completed**
 - Pure Al-Stabilized Cable (Hitachi, Japan) – **Completed.**
 - **Production Solenoid: (200m)**
 - Superconducting Wire (Furukawa, Japan) – **Completed**
 - Rutherford Cable (Furukawa, Japan) – **Completed**
 - Ni-doped Al-Stabilized Cable (Furukawa, Brazil) – **Completed**
 - **Detector Solenoid 1: (200m)**
 - Superconducting Wire (Furukawa, Japan) - **Completed**
 - Rutherford Cable (Furukawa, Japan) – **Completed**
 - Pure Al-Stabilized Cable (Furukawa, Brazil) – **Completed**
 - **Detector Solenoid 2: (200m)**
 - Superconducting Wire (Hitachi, Japan) – **Completed**
 - Rutherford Cable (Hitachi, Japan) – **Completed**
 - Pure Al-Stabilized Cable (Hitachi, Japan) – **Completed**



TS	DS1	DS2	PS
14x0.67mm	12x1.466mm	8x1.303mm	32x1.466mm
Cable size: 9.85x3.11mm	Cable size: 20.1x5.27mm	Cable size: 20.1x7.03mm	Cable size: 30.1x5.52mm

Overview of Prototype Phase

- For each of the 4 procurements, three hold points were placed throughout the development process.
- At each hold point, test data and samples are sent to Fermilab from the various vendors. Tests are performed at Fermilab and compared to vendors' results. After an internal review, Fermilab releases the hold point and allows vendors to proceed with the next development phase or final shipment of the conductor.
- Frequent conference calls were done throughout the process to monitor progress and discuss technical details.
- Fermilab visited all the vendors at crucial times of the development process.

Time schedule for TS conductors (Base quantity ; 3000m)

Process	2013												2014	
	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Jan.	
Procurement	→													
Single billet and wire	↔	↔												
Multi billet and wire		↔	↔	↔	↔									
Cabling in USA					↔	↔	↔	↔						
Procurement of Al		↔	↔	↔	↔	↔	↔	↔						
Conformal extrusion & cold work													↔	

ROUND WIRE

Wire diameter *
Wire ovality *
Critical Current *
n-Value *
Cu RRR *
Cu-SC ratio *
Twist pitch length and direction *
Filament diameter and spacing *
Sharp bent *
Eddy current

RUTHERFORD CABLE

Rutherford Cable thickness *
Rutherford Cable width *
Cable lay direction *
Cable transposition length *
Rutherford cable Bend test
Mechanical stability *
Residual twist
Surface condition
Crossovers or broken strands
Sharp edges *
Critical Current *
Cu RRR *

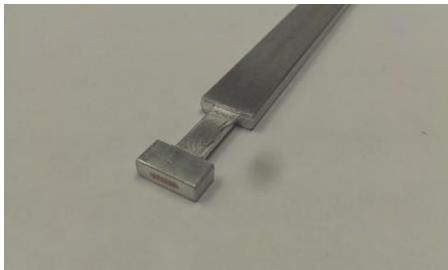
STABILIZED CABLE

Stabilized Cable thickness *
Stabilized Cable width *
Conforming parameters
Surface condition of the cable after conforming
Surface condition of the final cable
Al-Cu Bonding strength *
Aluminum RRR before conforming
Aluminum yield at 300 K after cold work *
Aluminum yield at 4.2 K after cold work
Aluminum RRR after cold work *
Critical Current *
Cu RRR *

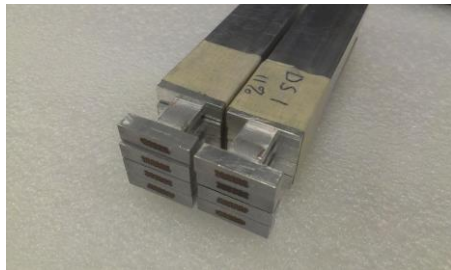
* Also measured at FNAL

Overview of Prototype Phase

- Based on this approach, 4 prototype cables were successfully procured.
- The project was awarded CD-3a in July 2014.
- The prototype campaign has proven to be extremely useful. Vendors had the chance to tweak their processes to deliver the best cable possible for the project. Numerous lessons learned along the way.
- *In summary:*
 - A total of 3,000m of TS cable were produced by Hitachi and fully accepted by Fermilab without any issue.
 - DS1 (Furukawa) and DS2 (Hitachi) cables met all our specs with the only exception of cross-section dimensions. Vendors are working on improving their cold-work dies to ensure production cables are within our specs.
 - PS cable (Furukawa) met all our specs with the exception of the RRR of the Al stabilizer which came in slightly below spec (500 instead of 600). The effect of this reduction has been investigated and found to be acceptable. A minor redesign of the cold-work die is needed for PS as well.
- *For further technical details, please refer to slides presented at CD-3a review*
<http://mu2e.fnal.gov/public/project/reviews/cd3a-review/index.shtml>



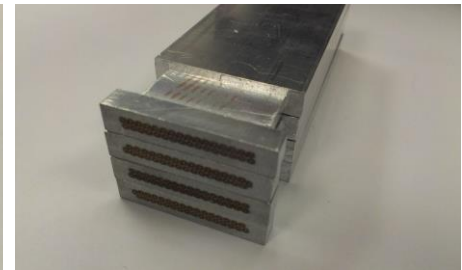
Transport Solenoid
Prototype cable



Detector Solenoid 1
Prototype cable



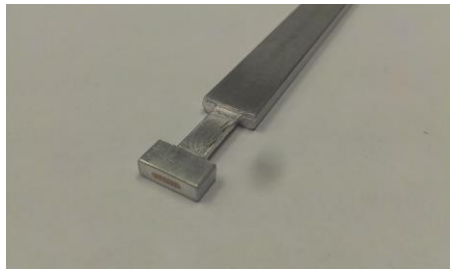
Detector Solenoid 2
Prototype cable



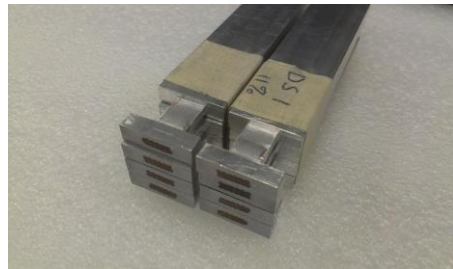
Production Solenoid
Prototype cable

Status of Production Orders

- The prototype orders were structured to include an option to manufacture production quantities of each of the four cables at a fixed price.
- TS, DS1, DS2 production orders have been placed; PS order is currently being finalized after recent vendor visit.
- All the production orders are being managed similarly to the prototype orders
 - One hold point after production of the NbTi wire is completed
 - One hold point after production of the Rutherford cable is completed
 - One hold point for each batch of Al-stabilized cable ready to be shipped to Fermi.
 - For PS only, we are requiring an extra 100m demo length and a first article (1700m) to be completely tested before approving the rest of the production.
- Regular (bi-weekly) conference calls with both vendors to monitor progress.
- Vendor visits during conforming/cold-work of at least the first article of each cable are scheduled.



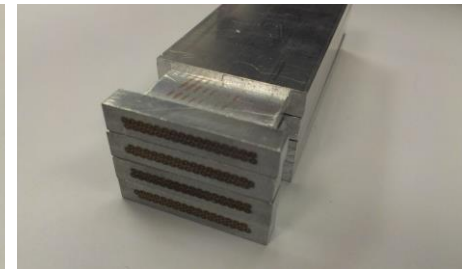
Transport Solenoid
Prototype cable



Detector Solenoid 1
Prototype cable



Detector Solenoid 2
Prototype cable



Production Solenoid
Prototype cable

Status of Production Orders

- Almost no changes in the procurement strategy with the respect to the prototype phase with only two exceptions.
 - TS wires will be cabled by New England under a contract signed between Hitachi cable and New England (Fermilab won't actively manage that contract as for the prototype phase)
 - Hitachi cable decided to outsource the cabling of DS2 wires to New England instead of performing it in house (in Japan).
- **Transport Solenoid:**
 - Superconducting Wire (Hitachi, Japan)
 - Rutherford Cable (New England, US) ←
 - Pure Al-Stabilized Cable (Hitachi, Japan)
- **Detector Solenoid 2:**
 - Superconducting Wire (Hitachi, Japan)
 - Rutherford Cable (New England, US) ←
 - Pure Al-Stabilized Cable (Hitachi, Japan)
- **Detector Solenoid 1:**
 - Superconducting Wire (Furukawa, Japan)
 - Rutherford Cable (Furukawa, Japan)
 - Pure Al-Stabilized Cable (Furukawa, Brazil)
- **Production Solenoid:**
 - Superconducting Wire (Furukawa, Japan)
 - Rutherford Cable (Furukawa, Japan)
 - Ni-doped Al-Stabilized Cable (Furukawa, Brazil)



TS	DS1	DS2	PS
14x0.67mm	12x1.466mm	8x1.303mm	32x1.466mm
Cable size:	Cable size:	Cable size:	Cable size:
9.85x3.11mm	20.1x5.27mm	20.1x7.03mm	30.1x5.52mm

Status of Production Orders

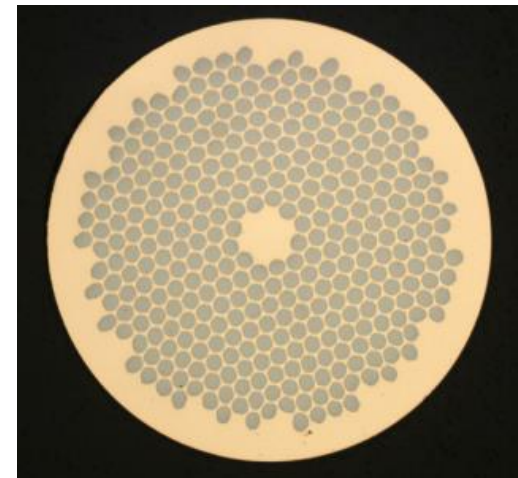
- About 75km of Al-stabilized cable are required by the experiment.
- About 62km are needed for coil winding and about 13km are procured as spares.
- In order to mitigate risk, the PS spare piece lengths have been increased from 1 to 3 in order to have enough conductor to re-manufacture the largest PS coil (only if necessary).

	Prototype Length	Production lengths needed for coil winding	Spare production lengths	Total Production Length
Transport Solenoid	3x1000m	14x1540mm 22x800	2x1540m 2x800m	~ 44km
Detector Solenoid 1	200m	8x1100m	1x1100m	~ 10km
Detector Solenoid 2	200m	3x1750m	1x1750m	~ 7km
Production Solenoid	200m	3x1700m 2x1300m 1x1500m	3x1700m	~ 14km

Status of Transport Solenoid order

- Hitachi is currently manufacturing a total of 768 km of TS wire.
- Wire production is being constantly monitored and is moving forward according to schedule.
- Billets will be delivered in three batches: #1-6 are scheduled to be completed in Oct, #7-12 in Nov and #13-16 in Dec.
- Samples from the first 6 billets expected to be delivered to Fermilab shortly for approval.
- The cabling of the TS wire will be performed at New England (US) via contract signed between Hitachi and New England.
- The cabling process is scheduled to start in late December.
- The 44km of TS Al-stabilized cable will be delivered in 4 batches, from 6/30/2015 to 12/31/2015.
- The order and the timeframe for delivery of the conductor has been chosen to match the order in which the coil units will be wound, tested and assembled.

Lot No.	Length @0.67mm (km)	Length for NEWT supply			Progress of manufacturing process							
		A (km)	B (km)	Total (km)	Extrusion D50mm	Drawing					Twist & Draw D0.67 mm	Clean & Cut & Wind
						D26	D14	D7	D2	D0.74		
HE6255	48.0	23..1	23.1	46.2	✓	✓	✓	✓	✓	✓	✓	✓
HE6256	48.0	23..1	23.1	46.2	✓	✓	✓	✓	✓	✓	✓	✓
HE6257	48.0	23..1	23.1	46.2	✓	✓	✓	✓	✓	✓	✓	✓
HE6258	48.0	23..1	23.1	46.2	✓	✓	✓	✓	✓	✓	✓	✓
HE6259	48.0	23..1	23.1	46.2	✓	✓	✓	✓	✓	✓	✓	✓
HE6260	48.0	23..1	23.1	46.2	✓	✓	✓	✓	✓	✓	✓	✓
HE6261	48.0	23..1	23.1	46.2	✓	✓	✓	✓	✓	✓		
HE6262	48.0	23..1	23.1	46.2	✓	✓	✓	✓	✓	✓		
HE6263	48.0	23..1	23.1	46.2	✓	✓	✓	✓	✓	✓		
HE6264	48.0	23..1	23.1	46.2	✓	✓	✓	✓	✓	✓		
HE6265	48.0	23..1	23.1	46.2	✓	✓	✓	✓	✓	✓	✓	
HE6266	48.0	23..1	23.1	46.2	✓	✓	✓	✓	✓	✓		
HE6393	48.0	23..1	23.1	46.2	✓	✓	✓	✓	✓	✓		
HE6394	48.0	23..1	23.1	46.2	✓	✓	✓	✓	✓	✓		
HE6395	48.0	23..1	23.1	46.2	✓	✓	✓	✓	✓	✓		
HE6396	48.0	23..1	23.1	46.2	✓	✓	✓	✓	✓	✓		
Total	768			739								

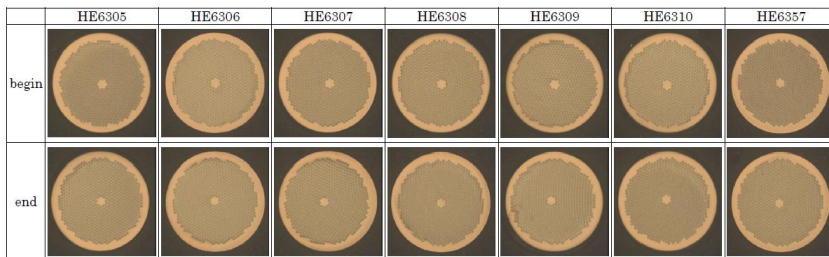
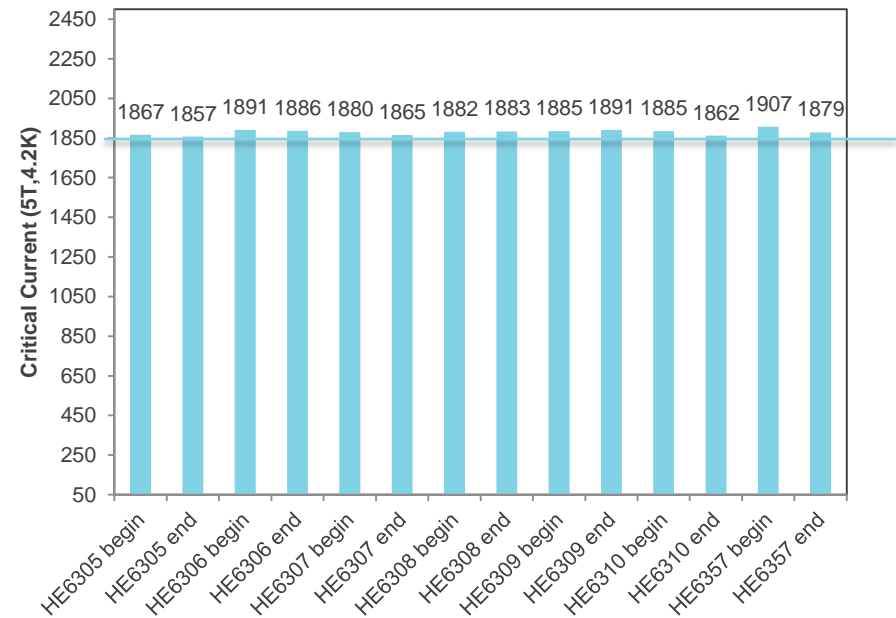


Cross-section of TS wire

Status of Detector Solenoid 2 order

- 7 billets for a total of 88km of wire completed on schedule.
- Samples received on time. Cold tested and approved by Fermi on schedule.
- During the prototype phase, cabling of DS2 wire was performed by Hitachi in Japan, whereas for the production quantities, cabling will be done in the US at New England.
- Procurement of Aluminum is scheduled to be completed by the end of October.
- Cabling started last week and is scheduled to be completed in November.
- After approval, the cable lengths will be shipped to Japan for conforming and cold work.
- 7km of DS2 Al-stabilized cable are scheduled to be delivered by 6/30/2015

Lot No.	Length (km) @1.303mm	Length for NEWT supply (km)			Progress of manufacturing process		
		A	B	Total	Drawing D1.44mm	Twist&Draw D1.303mm	Clean& Cut&Wind
HE 6305	13.0	6.05	6.05	12.1	✓	✓	✓
HE 6306	13.0	6.05	6.05	12.1	✓	✓	✓
HE 6307	13.0	6.05	6.95	13.0	✓	✓	✓
HE 6308	13.0	6.05	6.05	12.1	✓	✓	✓
HE 6309	13.0	6.05	6.95	13.0	✓	✓	✓
HE 6310	13.0	6.05	6.95	13.0	✓	✓	✓
HE 6357	11.0	6.05	4.05	10.1	✓	✓	✓
Total	88			85.4			



Status of DS1 and PS orders

Detector Solenoid 1

- DS1 wires are currently being manufactured in Japan by Furukawa Electric.
- This process is scheduled to be completed by the end of November.
- Cabling will be performed in Japan by Furukawa and expected to be completed by the end of January.
- Procurement of Aluminum is completed. Tests to be started soon.
- 9.9km of DS1 Al-stabilized cable are scheduled to be delivered by 6/30/2015.

Production Solenoid

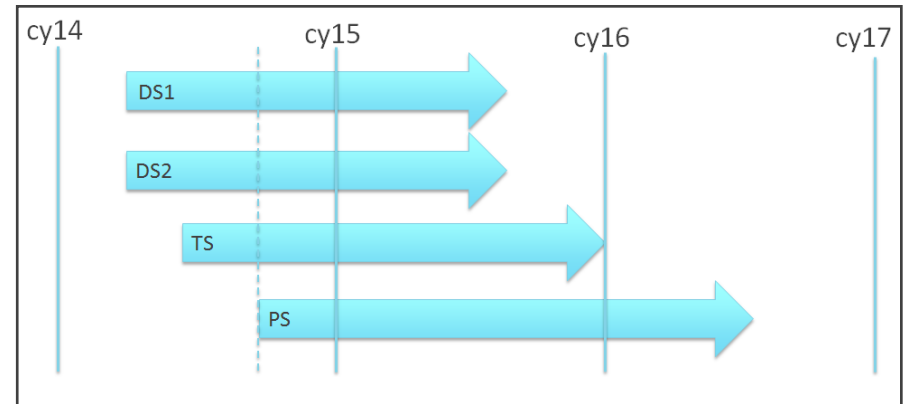
- PS production order will be placed shortly.
- Vendor visited Fermilab recently to iron out the final details, including additional piece lengths and hold points.
- First article is expected in 12-13 months.
- The overall process is estimated to take approximately 19-20 months.



Furukawa's facilities in Curitiba, Brazil

Conclusions

- **Detector Solenoid 1:**
 - Superconducting Wire (Furukawa, Japan) - **In progress**
 - Rutherford Cable (Furukawa, Japan) – **Not started**
 - Pure Al-Stabilized Cable (Furukawa, Brazil) – **Not started**
- **Detector Solenoid 2:**
 - Superconducting Wire (Hitachi, Japan) – **Completed**
 - Rutherford Cable (New England, US) – **In progress**
 - Pure Al-Stabilized Cable (Hitachi, Japan) – **Not started**
- **Transport Solenoid:**
 - Superconducting Wire (Hitachi, Japan) – **In progress**
 - Rutherford Cable (New England, US) – **Not started**
 - Pure Al-Stabilized Cable (Hitachi, Japan) – **Not started**
- **Production Solenoid:**
 - Superconducting Wire (Furukawa, Japan) – **Not started**
 - Rutherford Cable (Furukawa, Japan) – **Not started**
 - Ni-doped Al-Stabilized Cable (Furukawa, Brazil) – **Not started**



Overview of production orders

- TS, DS1 and DS2 orders placed. PS order to be placed shortly.
- All placed orders are moving forward on or slightly ahead of schedule.
- According to present schedules, all the conductors will be ready for delivery to the magnet vendors with a generous amount of float.