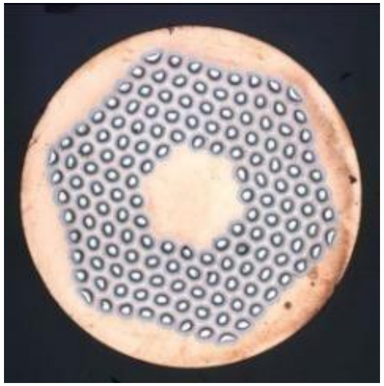
FCC-MDP-EuroCirCol Coordination Meeting
January 16, 2017

Cable design approach and experience at FNAL

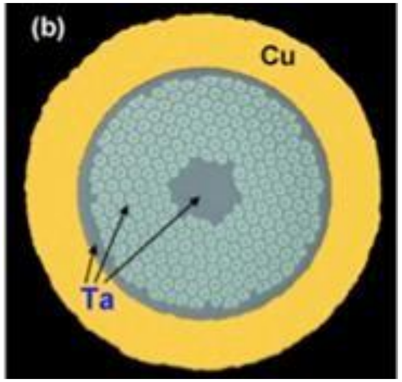
E. Barzi

Cabling Experience at FNAL

Strands



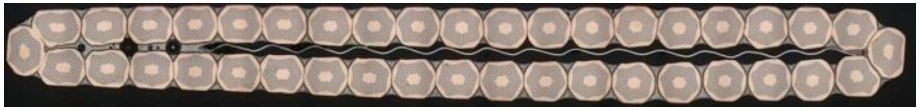
Nb_3Sn

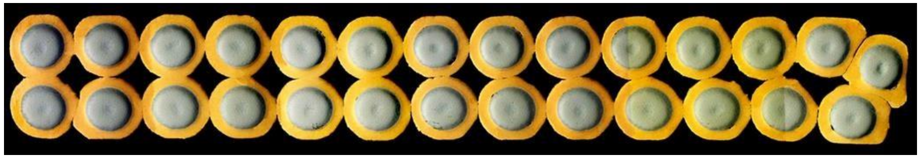


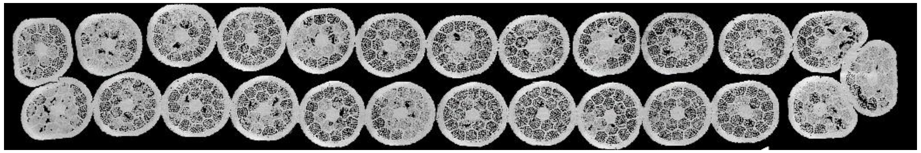
Nb_3Al

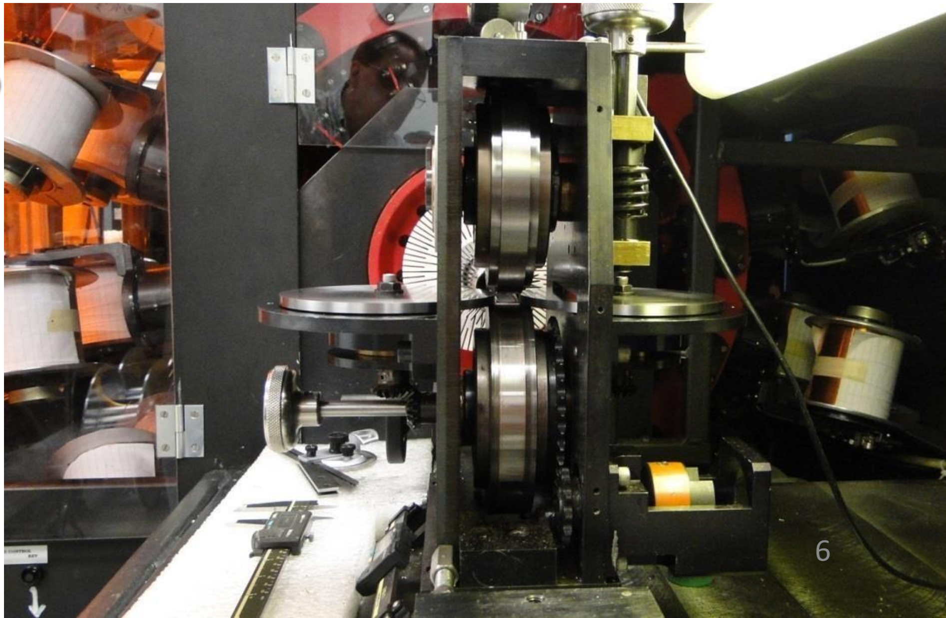
Bi-2212

Rutherford-type Cables



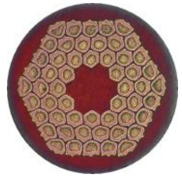




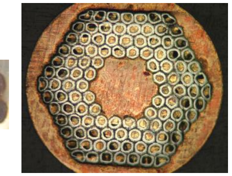


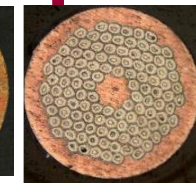
Nb_3Sn Strand and Cable Past Landscape

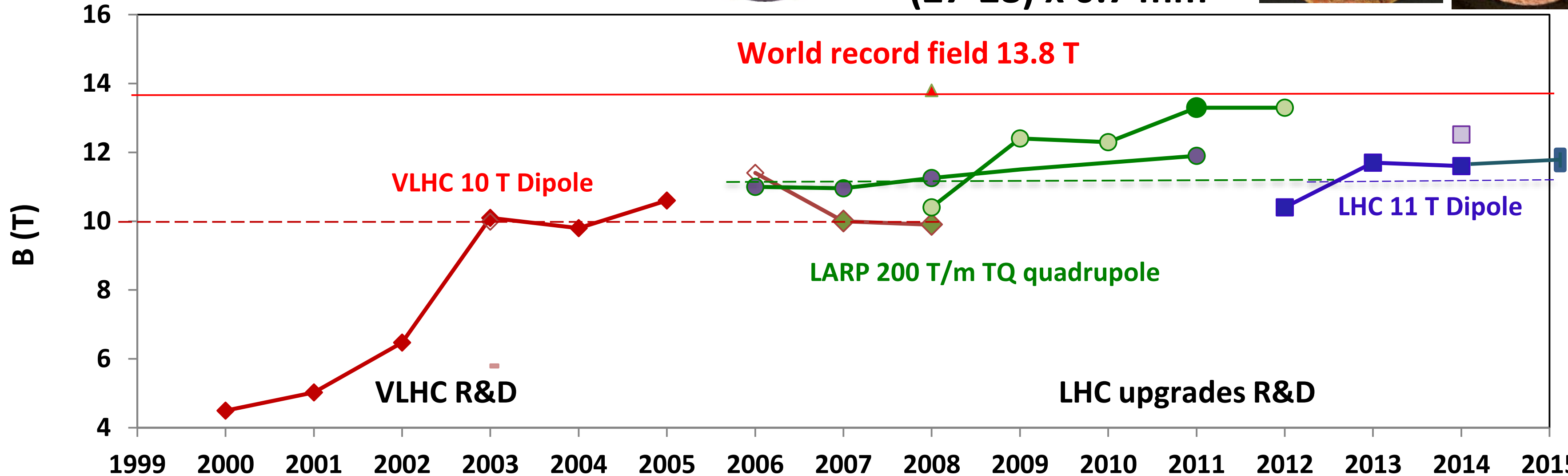
60 x 0.7 mm

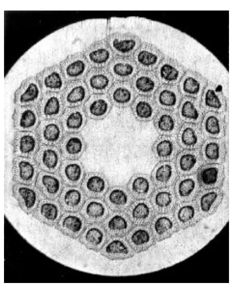


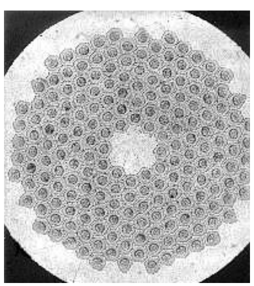
(27-28) x 0.7 mm

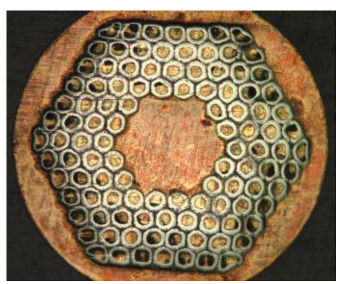


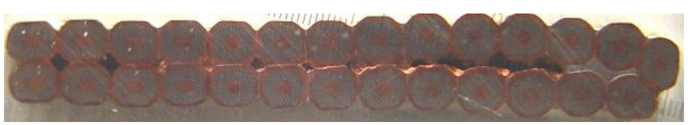




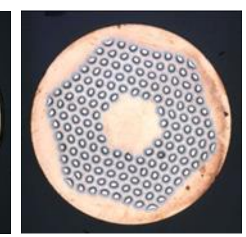


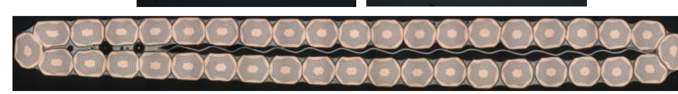






(27-28) x 1.0 mm





40 x 0.7 mm

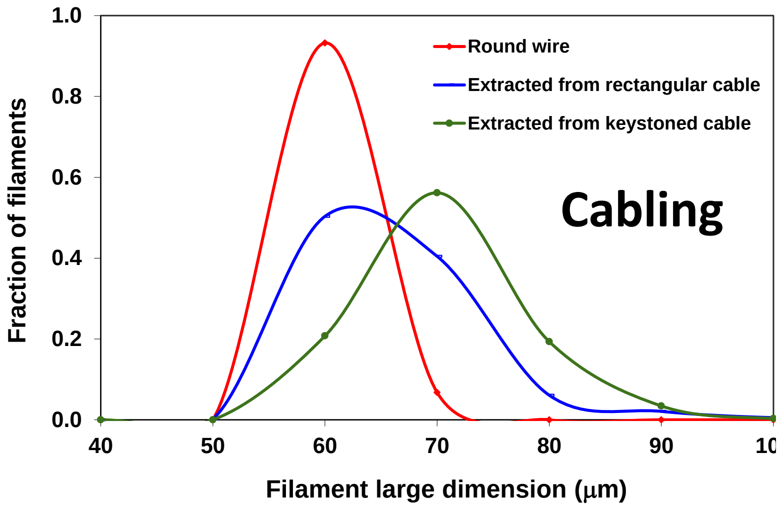
Outline

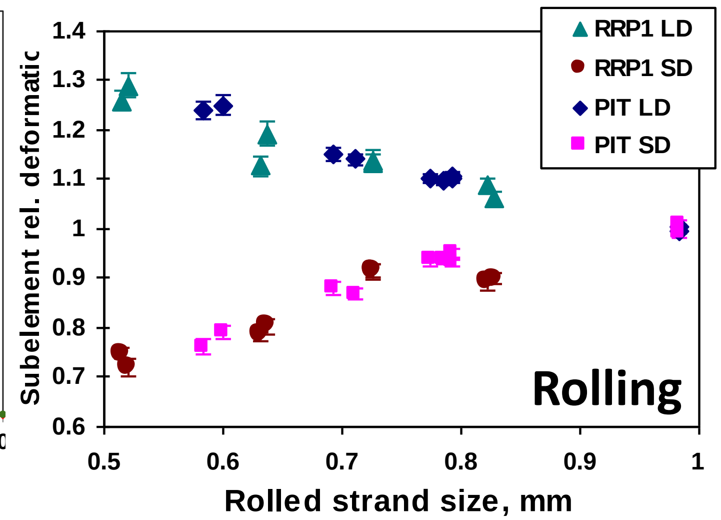
- **Introduction - What happens to Nb_3Sn in cabling.**
- **Approach to Cable Design.**
- **Approach to Cable Fabrication.**
- **Approach to Cable Quality Control.**
- **Approach to Cable Characterization.**
- **Experience – Examples.**
- **Conclusions.**

Effect of Cabling on Round Strand Layout

Subelement Deformation

$$\varepsilon_{SE} = \frac{d_{max} - d_{min}}{d_0}$$

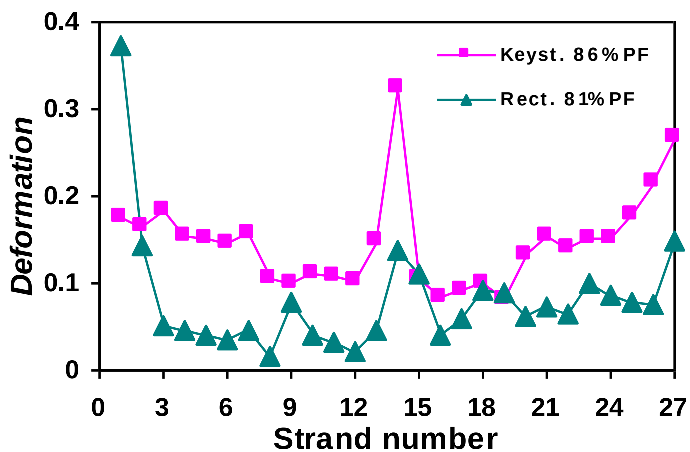


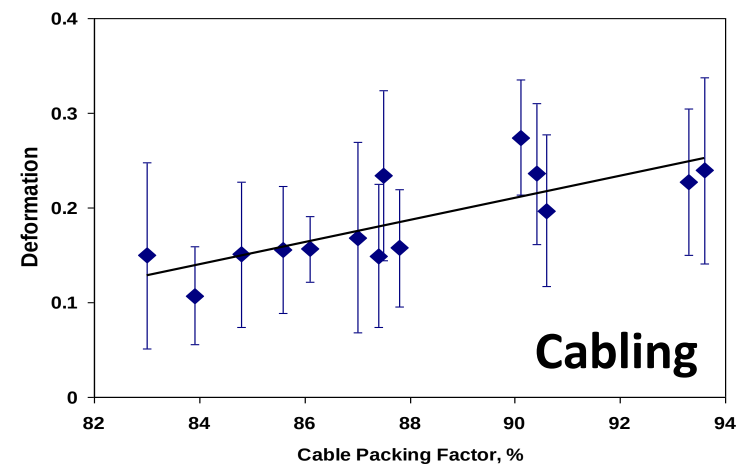


Strand Deformation

$$\varepsilon_{str} = \frac{d_{max} - d_{min}}{d_0}$$

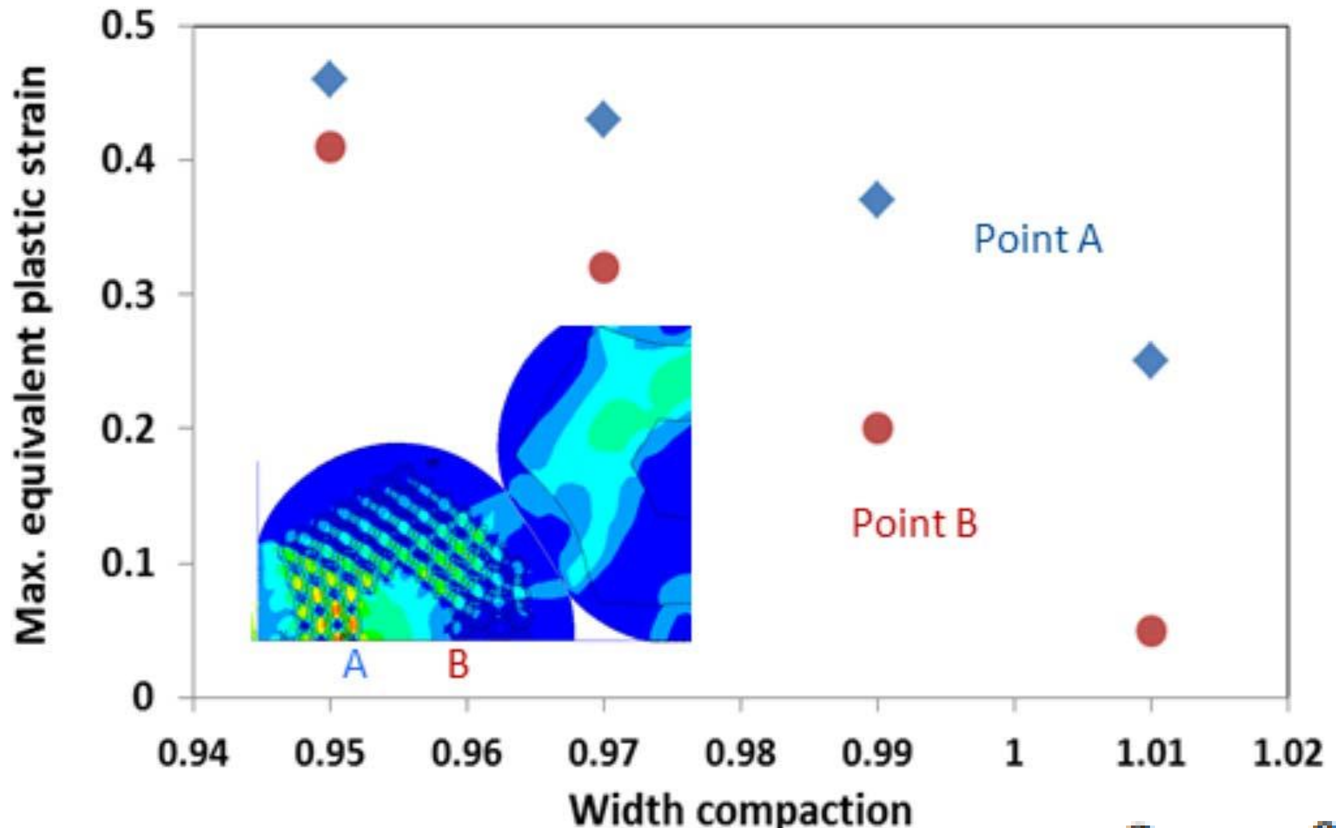
thin  thick





Plastic Strain produced by Rutherford Cabling

Strain sensitivity to Width compaction

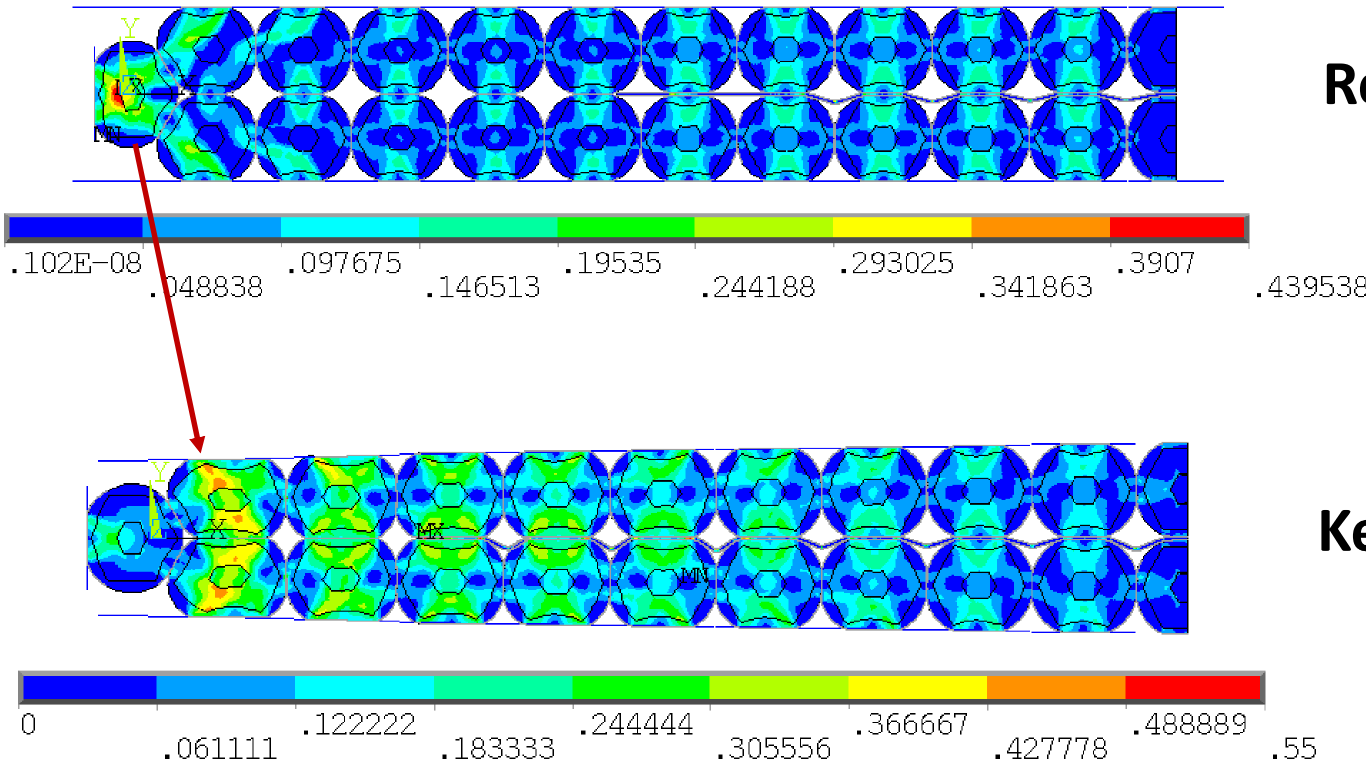


$$R_w \cong \frac{2w \cdot cos\theta}{N \cdot D}$$

E. Barzi et al., "FEM Analysis of Nb-Sn Rutherford-type Cables", **IEEE Trans. Appl. Sup., V. 22, No. 3, pp. 4903305 (2012).**

E. Barzi et al., "Superconducting strand and cable development for the LHC upgrades and beyond", **IEEE Trans. Appl. Sup., V. 23, No. 3 (2013).**

Effect of Keystoning on Plastic Strain

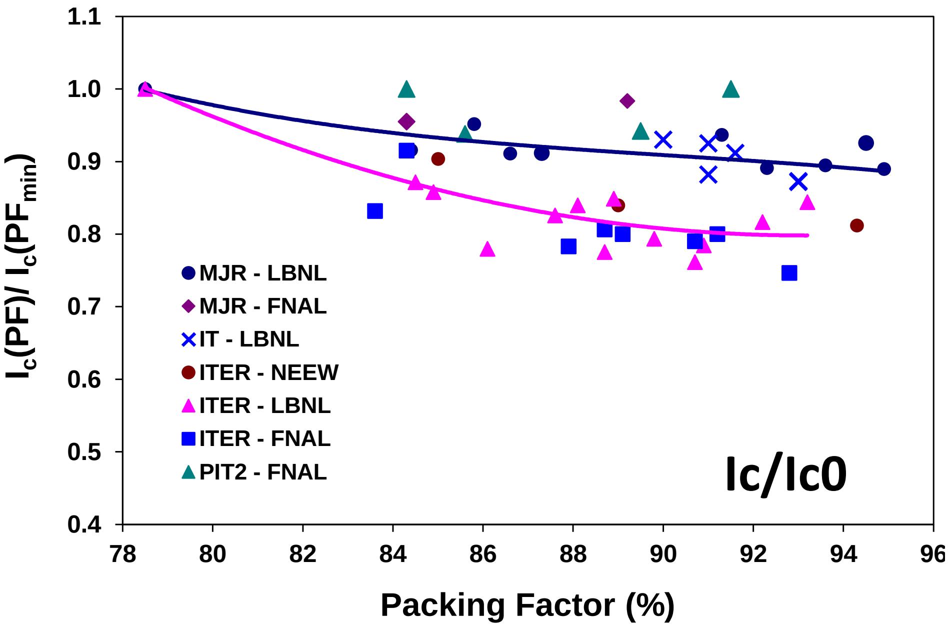


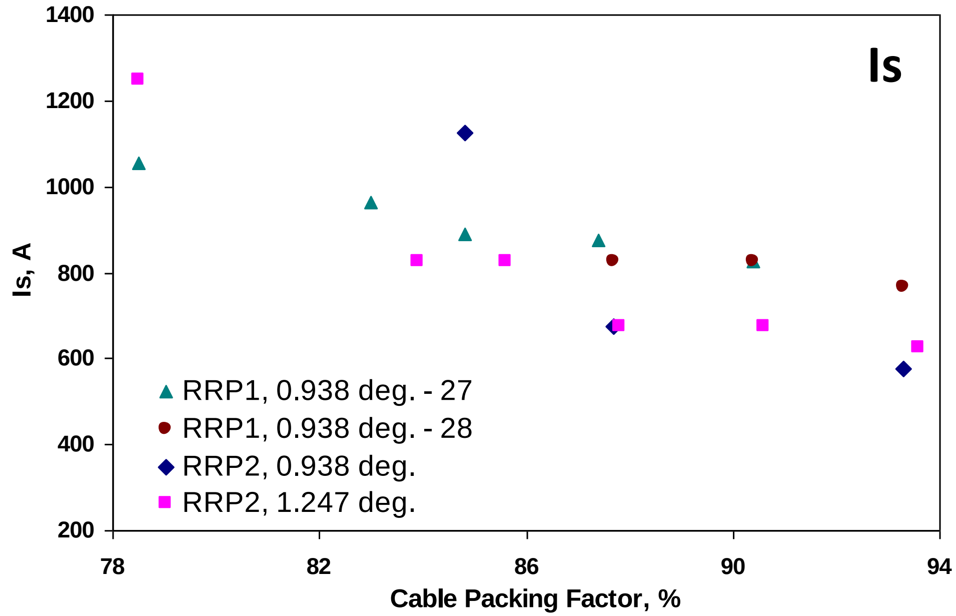
Rectangular stage

Keystoned stage

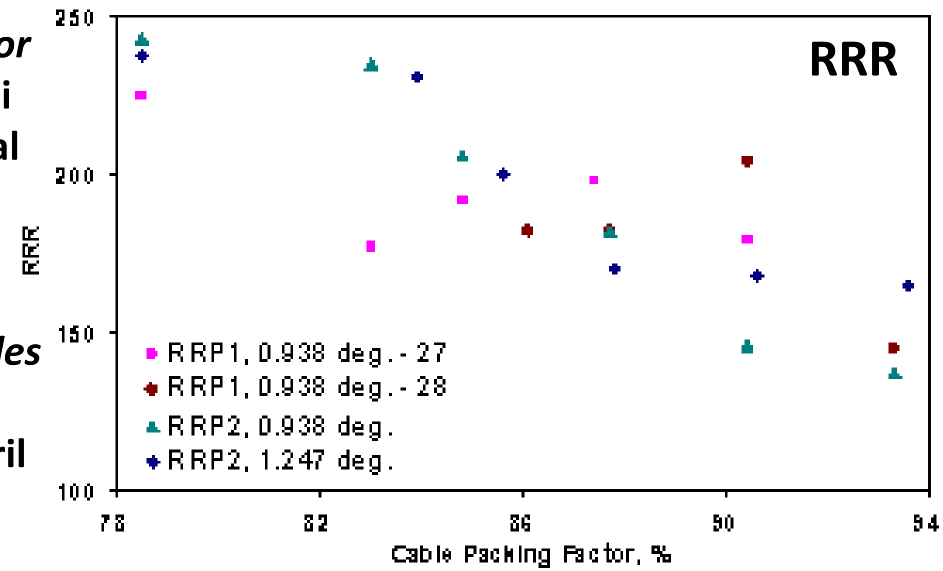
E. Barzi et al., "Superconducting strand and cable development for the LHC upgrades and beyond", **IEEE Trans. Appl. Sup., V. 23, No. 3 (2013).**

Effect of Cabling on Transport Properties



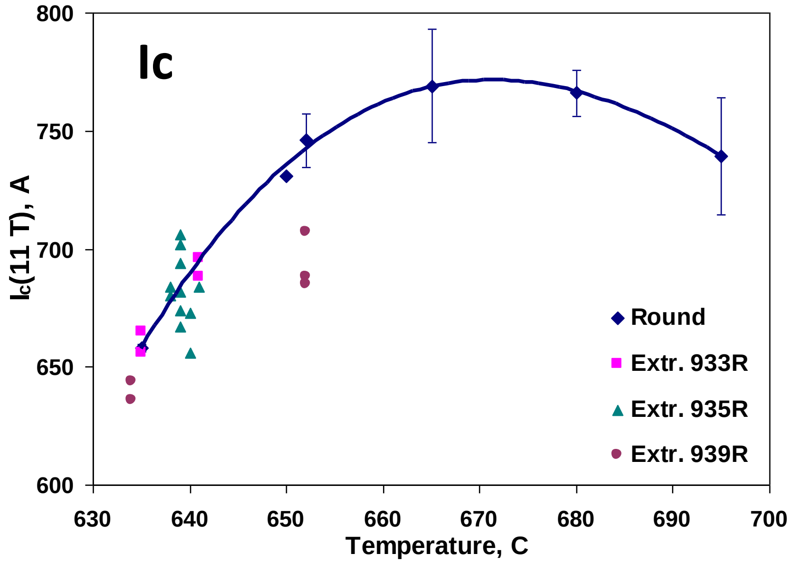


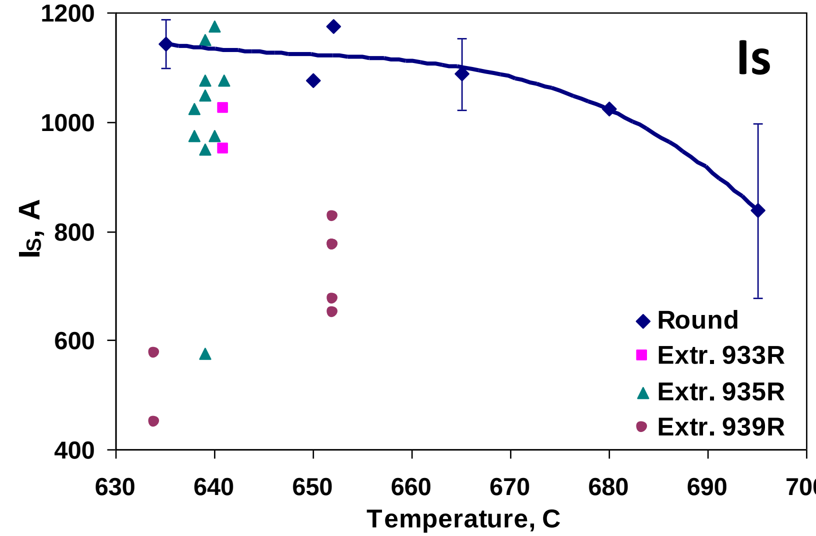
"Development and Study of Rutherford-type Cables for High-field Accelerators Magnets at Fermilab", E. Barzi et al., Superconductor Science and Technology, special issue, V. 17, No. 5, p. 213 (2004).

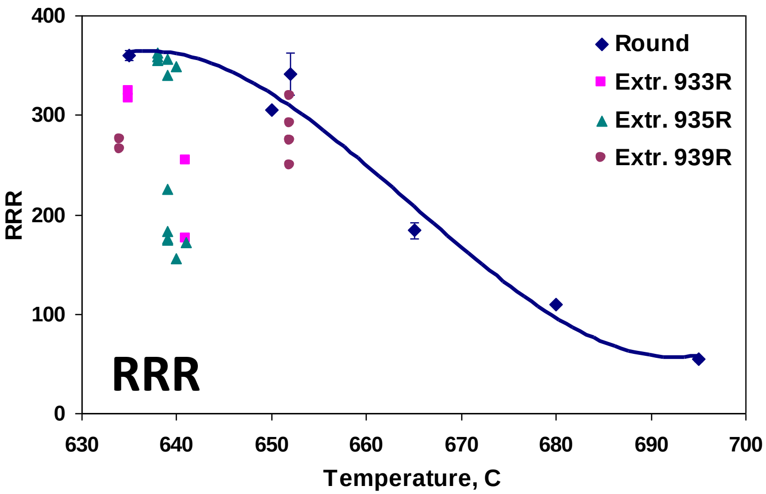


"Research and Development of Nb_3Sn Wires and Cables for High-Field Accelerator Magnets", E. Barzi, A.V. Zlobin, IEEE Trans. on Nuclear Science, vol. 63 (2), April 2016, pp. 783-803.

The Importance of Statistics







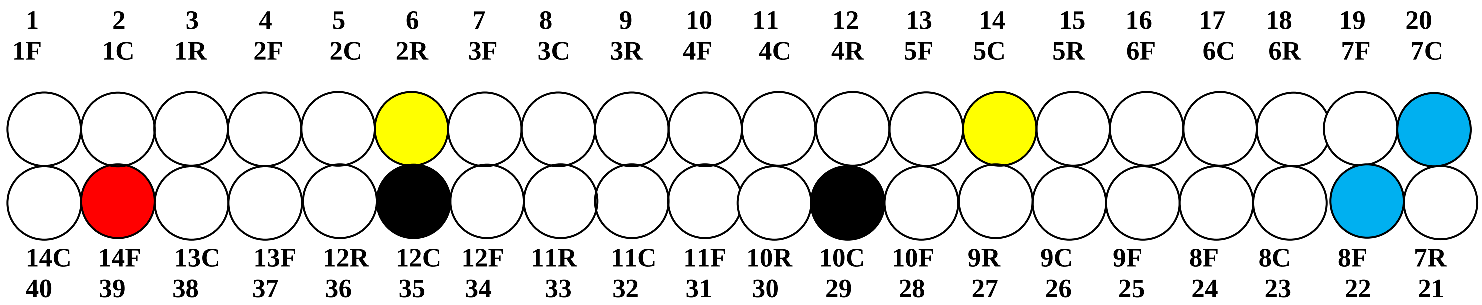
Cable ID	Techn ology	Impreg nation	No. quenches	Cable Ave. I_q, kA	Ave. I_q/ strand, A	Min. I_q/ strand, A	R_{splice}, nΩ
926R (SQ)	MJR	Y	12	18.4	918	898	2.9
"	"	N	13	18.9	943	892	4.8
928R-B (TQ)	MJR	Y	12	19.8	734	697	3.1-3.9
"	"	N	16	19.7	729	688	2.3
928R-B (TQ)	"	N	14	20.4	755	732	2.8-3.2
932R-A (TQ)	"	N	14	23.5	869	851	2.5
935R (SR)	RRP	Y	18	18.1	906	807	2.7-2.5
"	"	N	16	18.7	935	878	2.9-3.1
942R (LR)	"	N	17	19.7	987	945	3.0-3.2
933R (TQ)	RRP	N	11	22.6	836	762	2.9-3.0
"	"	N	15	20.1	745	583	3.2-3.4
939R (TQ)	"	N	15	19.1	708	666	2.6-2.8
"	"	N	16	18.7	693	650	4.1-4.4
940R (TQ)	"	N	17	21.1	780	721	3.0
946R (TQ)	"	N	9	21.9	811	768	2.2-4
947R (TQ)	"	N	13	23.3	864	848	1.7

***"RRP Nb_3Sn Strand Studies for LARP"*, Emanuela Barzi, Rodger Bossert, Shlomo Caspi, Dan Dietderich, Paolo Ferracin, Arup Ghosh, Daniele Turrioni, IEEE Trans. Appl. Sup., V. 17, No. 2, p. 2607 (2007).**

Cable Specs Design

- **Factors used in selecting an initial cable geometry:**
  - **Strand size appropriate to achieve required magnet transfer function.**
  - **Deformation of small edge 1-h/2d ≤ 20%.**
  - **Large edge compacted by ~2% for mechanical stability.**
  - **Width compaction, i.e. cable width/undeformed width > 1.**
  - **Cable packing factor ~ 87-88%.**

DM-CF-02-0b Cable Map - Example

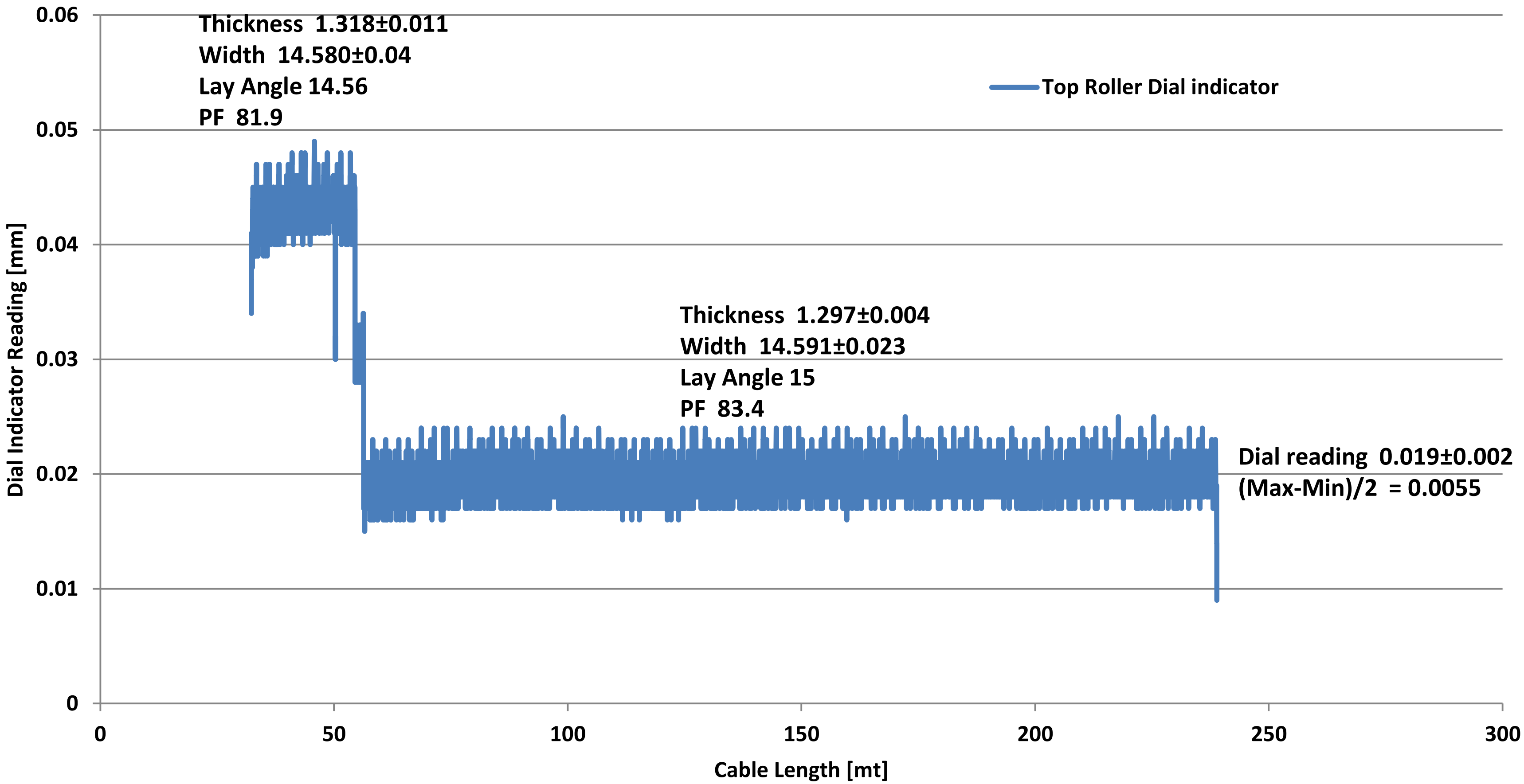


Strand	Wheel						
No.	Position	Color	Dia	Length, m			Billet ID
				Inner	Middle	Outer	
1	1f	NC	0.698/0.700	67 / 361			13538-1c / 13538-7
2	1c	NC	0.702/0.702		67 / 361		13613-5b2 / 13613-5a
3	1r	NC	0.700/0.700			67 / 361	13538-8b / 13538-4
4	2f	NC	0.699/0.703	67 / 361			13538-1c /13613-5b3
5	2c	NC	0.698/0.700		67 / 361		13538-4 /13538-8b
6	2r	yellow	0.698/0.701			67 / 361	13538-8b / 13613-5b1
7	3f	NC	0.700/0.698				13613-1 / 13538-8a
8	3c	NC	0.702/0.703		67 / 361		13538-4 / 13613-5b1
9	3r	NC	0.702/0.700			67 / 361	13613-4 / 13538-2b2
10	4f	NC	0.703/0.702	67 / 361			13613-1 / 13613-5b2
11	4c	NC	0.698/0.698		67 / 361		13613-4 / 13538-2b2
12	4r	NC	0.699/0.702			67 / 361	13538-1c / 13613-5b2
13	5f	NC	0.700/0.700	67 / 361			13538-1c / 13538-2b1

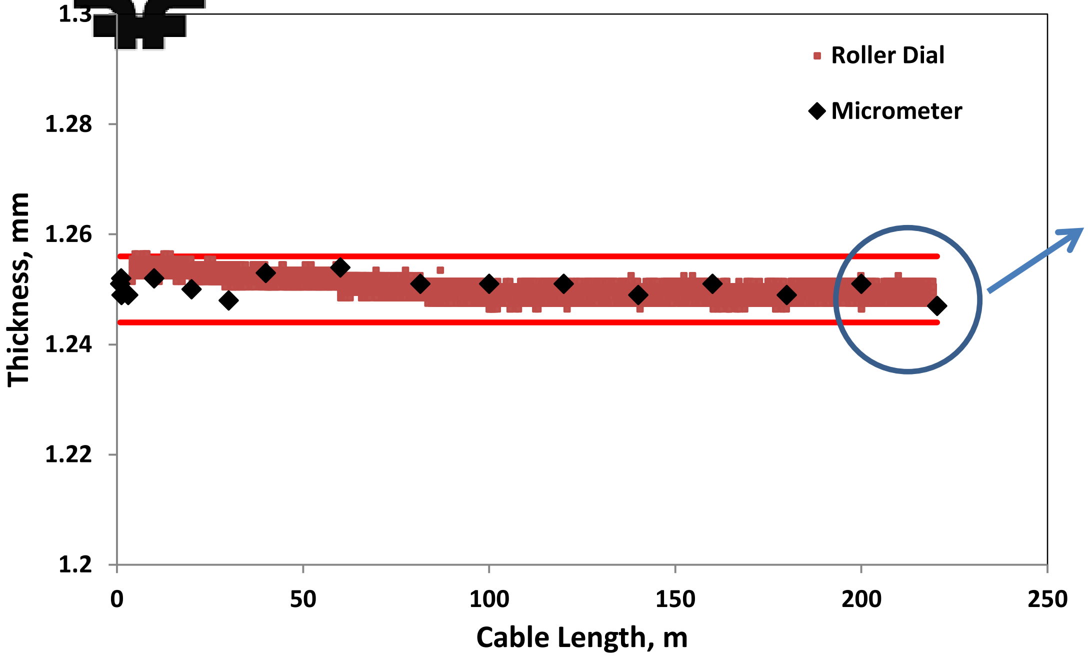
The following billets were used: 13538-1a, -1b1, -1b2, -2a, -2b1, -2b2, -4, -7, -8a, -8b, and 136131-5a, -5b, -5b1, -5b2, -5b3.

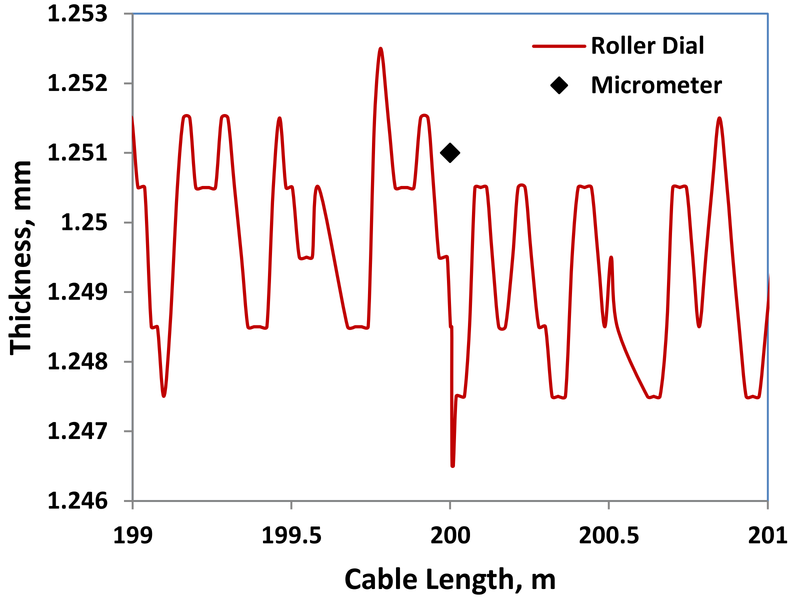
Example of Cable Measurements

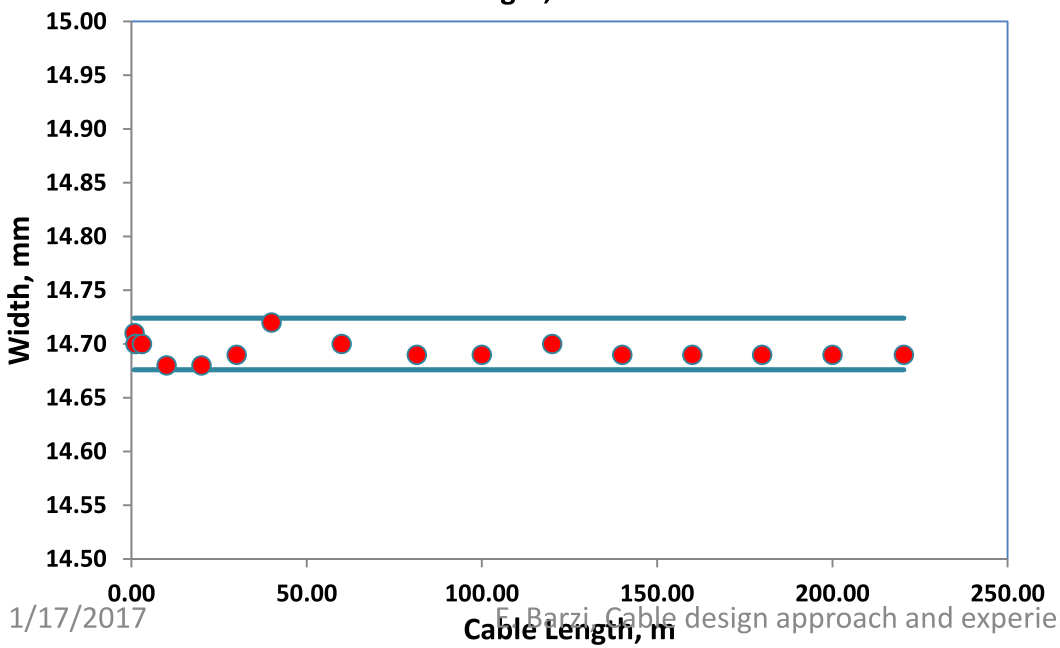
Traveler	Type	Strand Design	No. strands	Strand size mm	Mandrel width mm	Cable width mm	Cable thickness mm	Lay angle °	PF %	SS Core	Length m
R&DT_110420_40_1_0	R	Cu	40	0.697	13.92	14.591±0.023	1.297±0.004	15	83.4	N	186



DM-CF-02-0b – MBH05 and MBH07



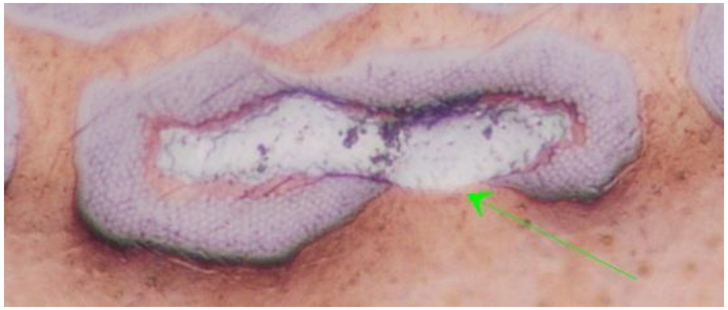


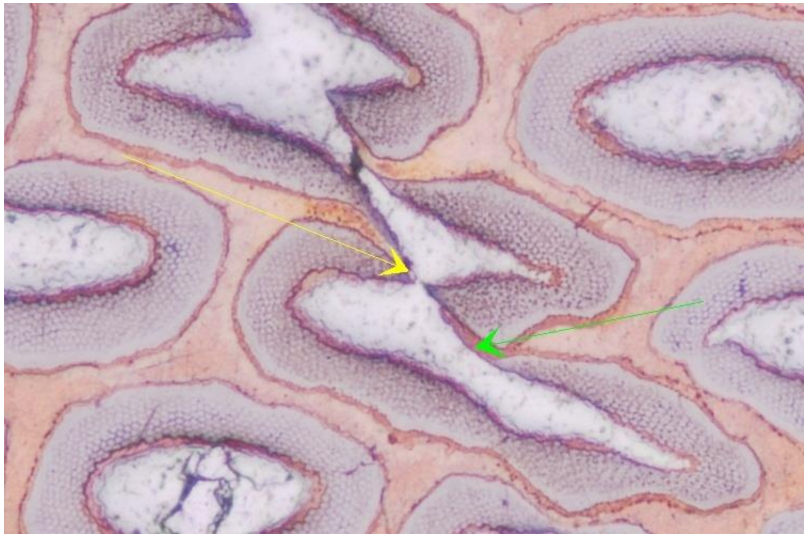


Upper roller diameter = 100 mm, periodicity of 0.31 m along cable length

Quality Control for RRP Wires

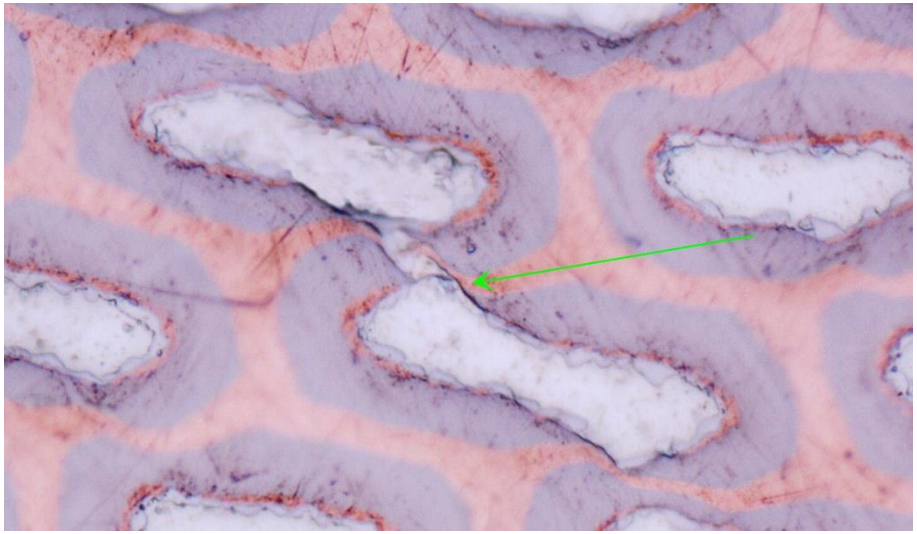
RRP subelements are prone to merging together when subject to plastic strain, as during cabling. Microscopic damage analyses are performed as part of cable quality control.

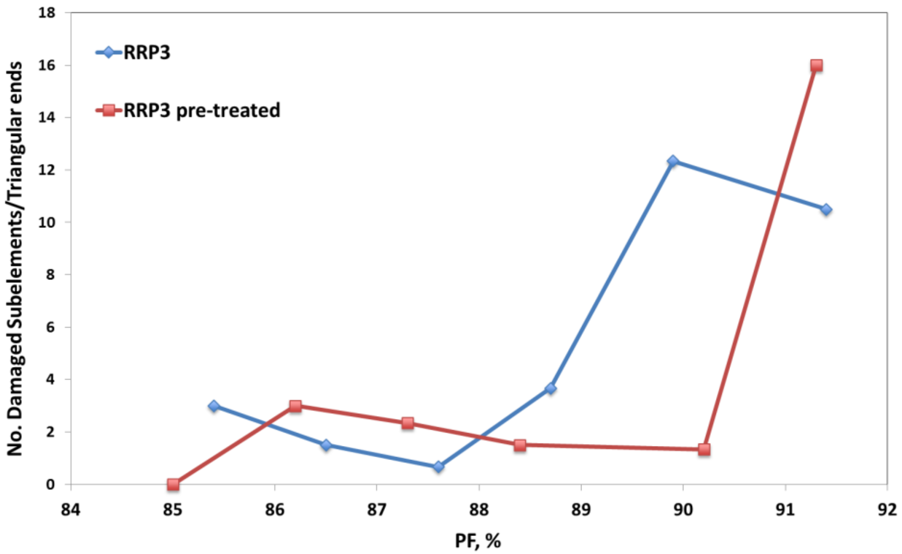




Pictures by Marianne Bossert

Example of Analysis – Performed on usually 6 cross sections / cable

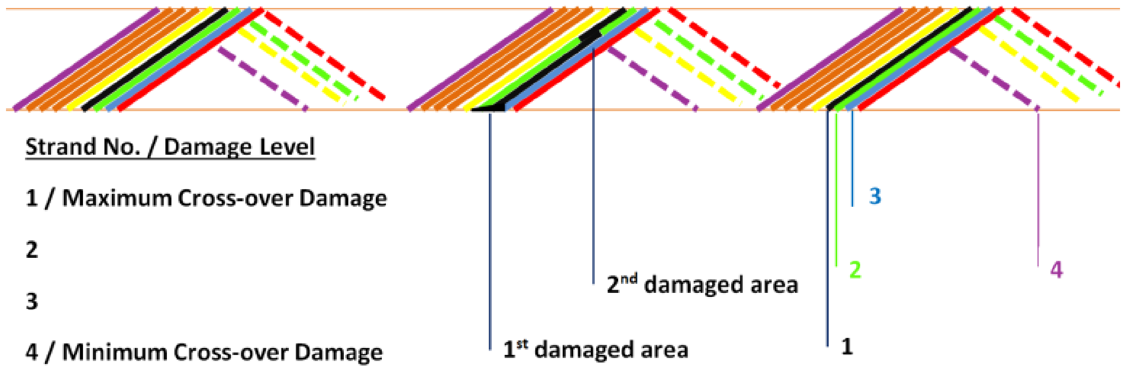


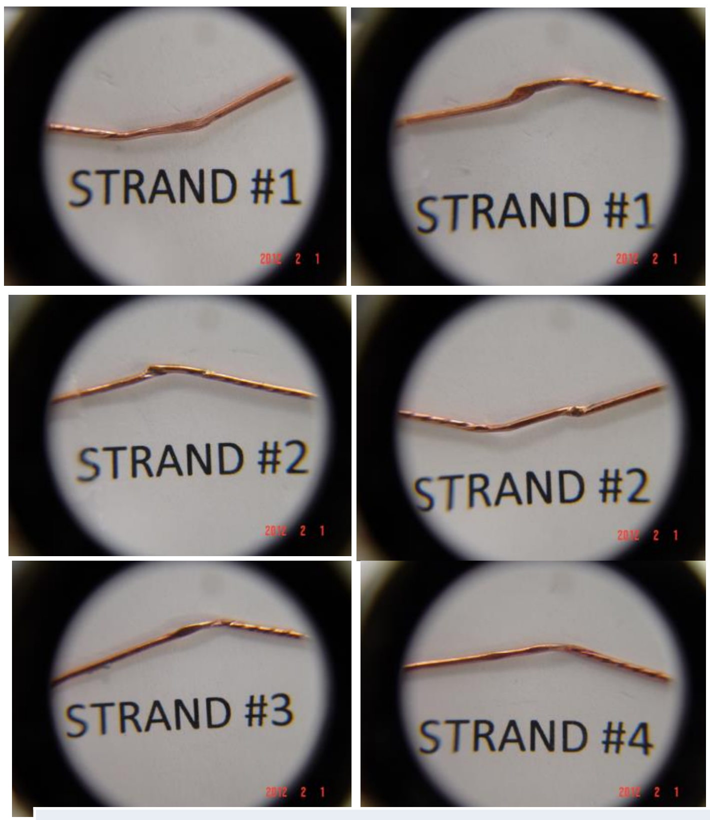


Example of results - Normalized No. of damaged subelements vs. Cabling packing factor.

Study of Cross-over Effects (1)

Schematic of cross-over layout in cable ID 1. Strands No. 1 and No. 2 crossed at an edge and re-crossed within the following half-pitch length.





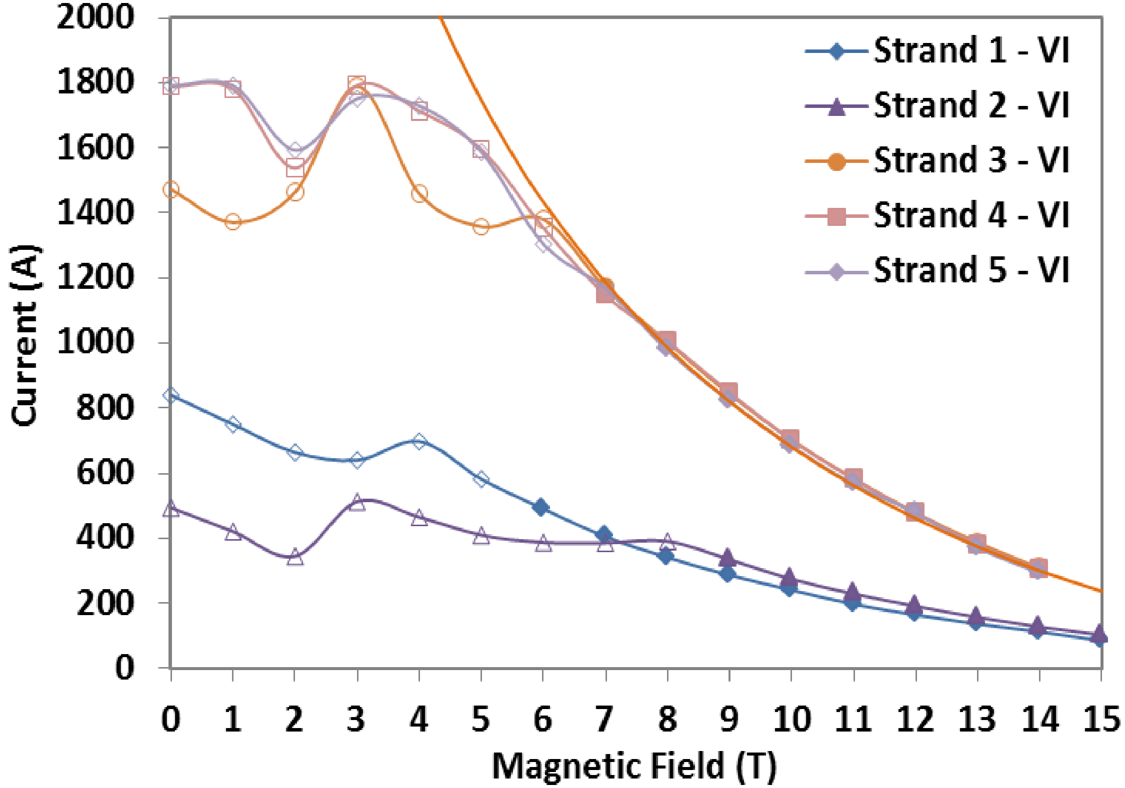
Picture of first damaged area, which led to quench (left), and second damaged area (right) on strand No. 1.

Picture of first damaged area (left) and second damaged area, which led to quench (right), on strand No. 2.

Picture of area in strand No. 3 closest to first damaged area (left), and picture of area in strand No. 4 closest to second damaged area (right).

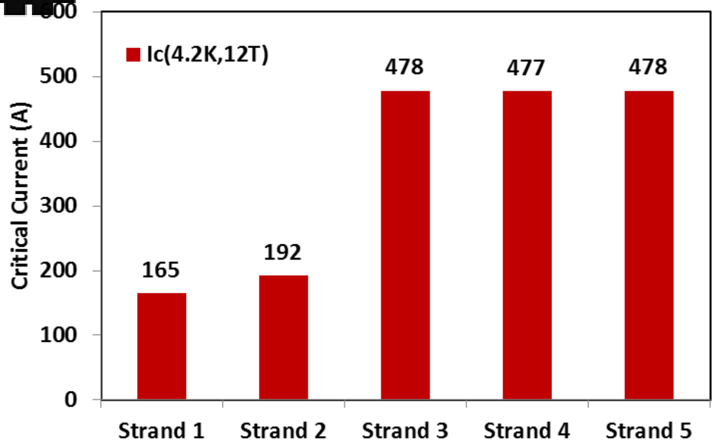
See also E. Barzi et al., "Superconducting strand and cable development for the LHC upgrades and beyond", accepted in IEEE Trans. Appl. Sup., V. 23, No. 3 (2013).

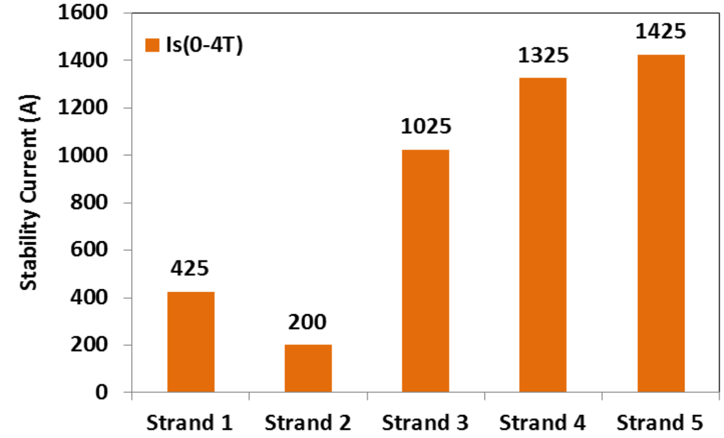
Study of Cross-over Effects (2)

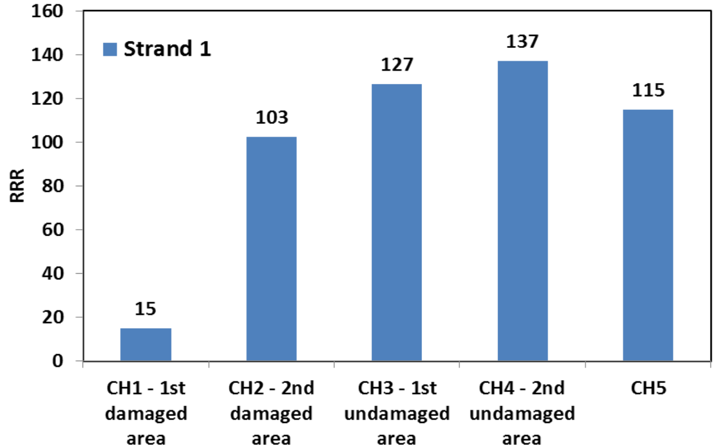


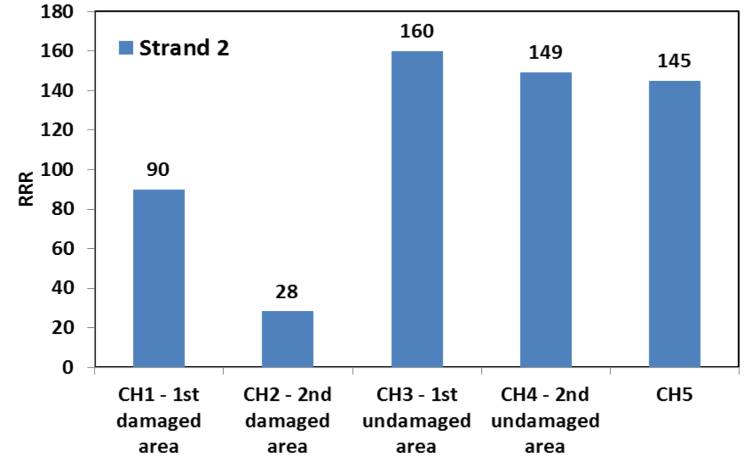
V-I **test results at 4.2 K of strands Nos. 1 to 5. Closed markers were used for I_c values, whereas open markers indicate the maximum current reached by samples that quenched prematurely.**

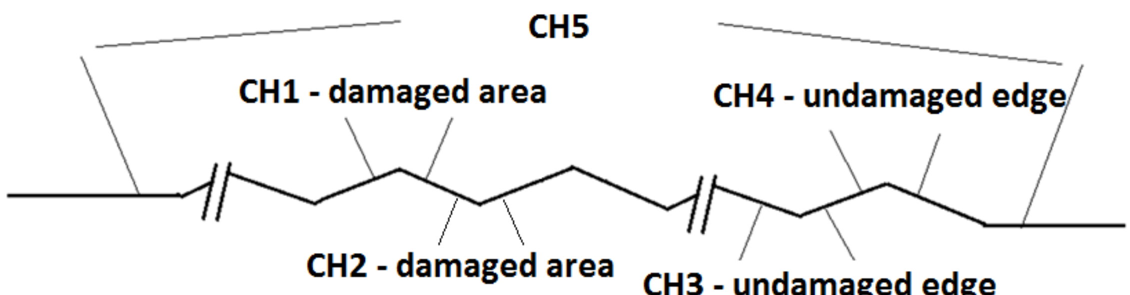
Study of Cross-over Effects (3)



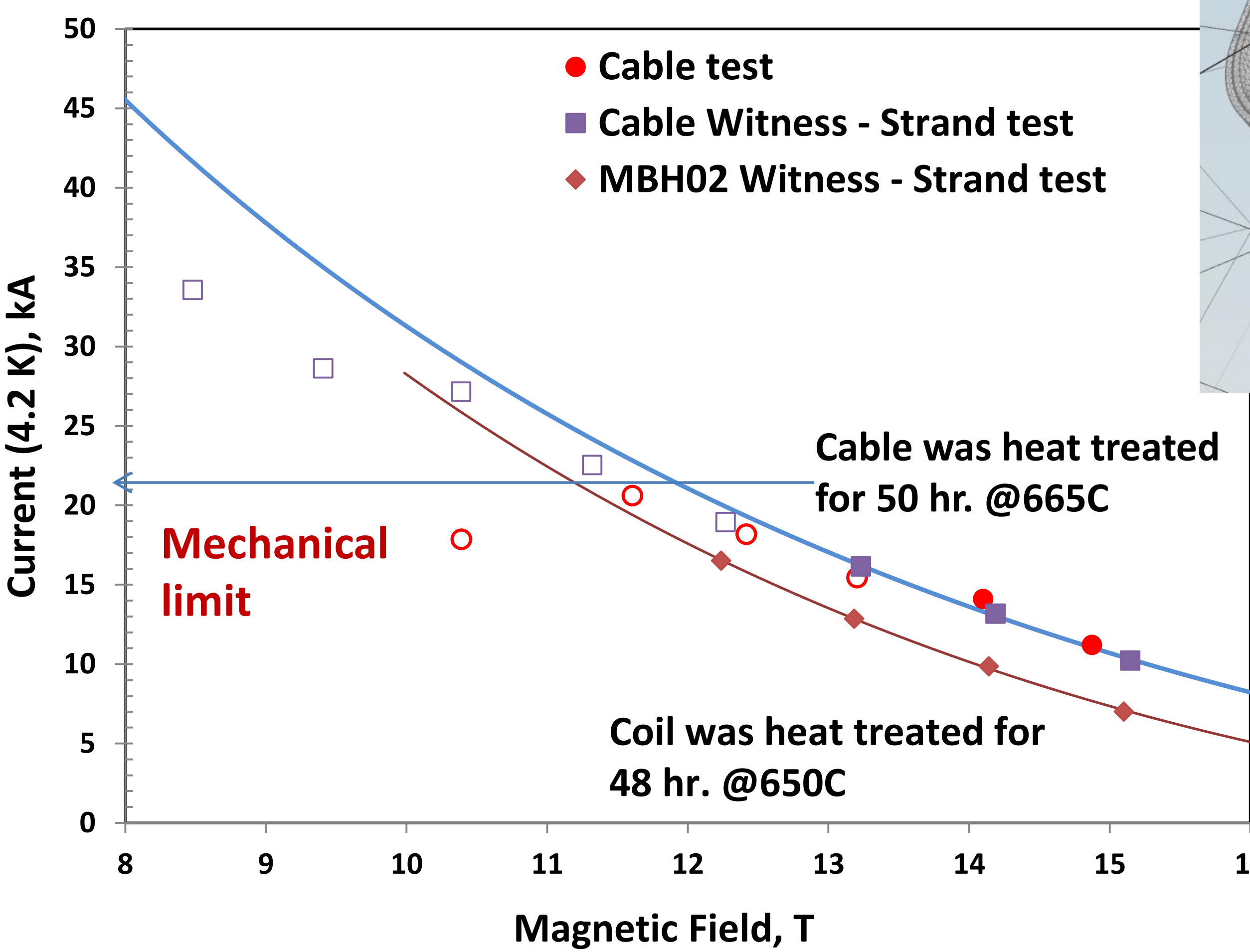


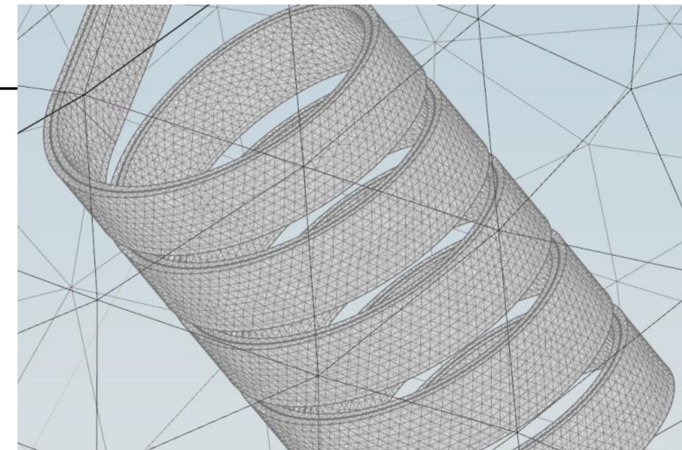






Test of 108/127 RRP Cable DM-CF-01-0b (MBHSP01) with SC Transformer





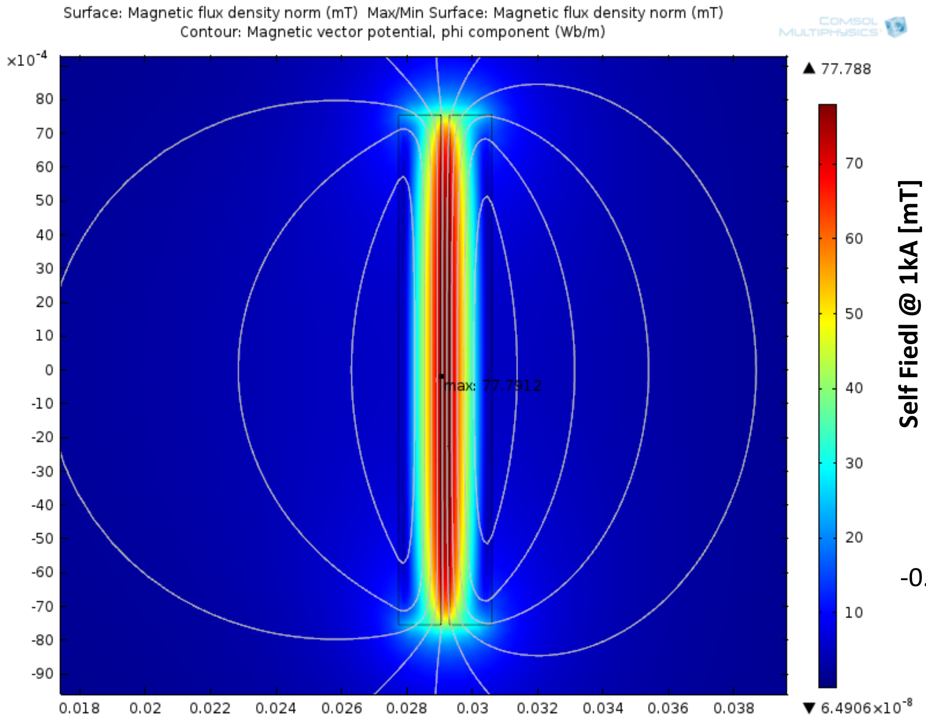
3D FEM Model

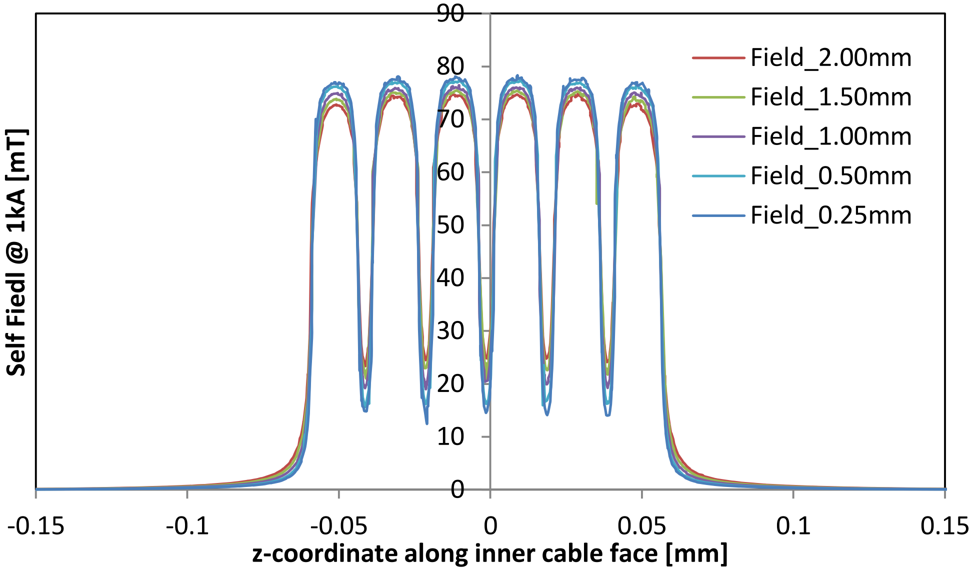
Cable Parameter	Value
Cable thickness	1.3 mm
Cable width	15.09 mm
Bifilar gap	0.25 mm

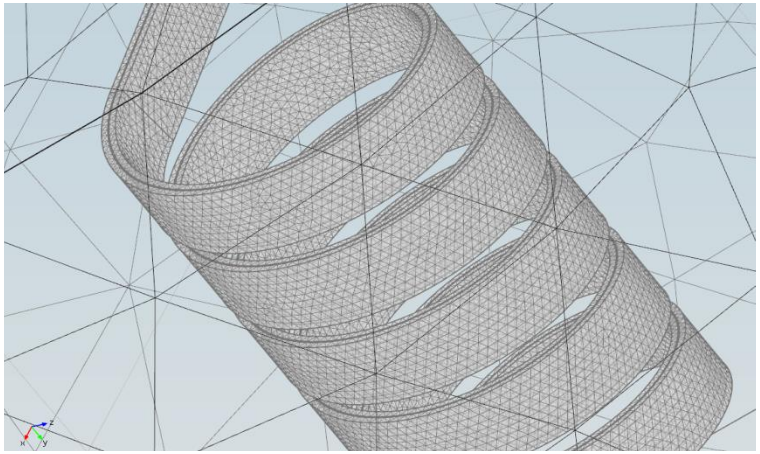
Self-field correction 0.078 T/kA

"Progress in Nb3Sn RRP Strand Studies and Rutherford Cable Development at FNAL", E. Barzi, D. Turrioni and A. V. Zlobin, IEEE Trans. Appl. Sup., article #6000808, V. 24, No. 3 (2014).

Self-Field Calculations for Cable Test





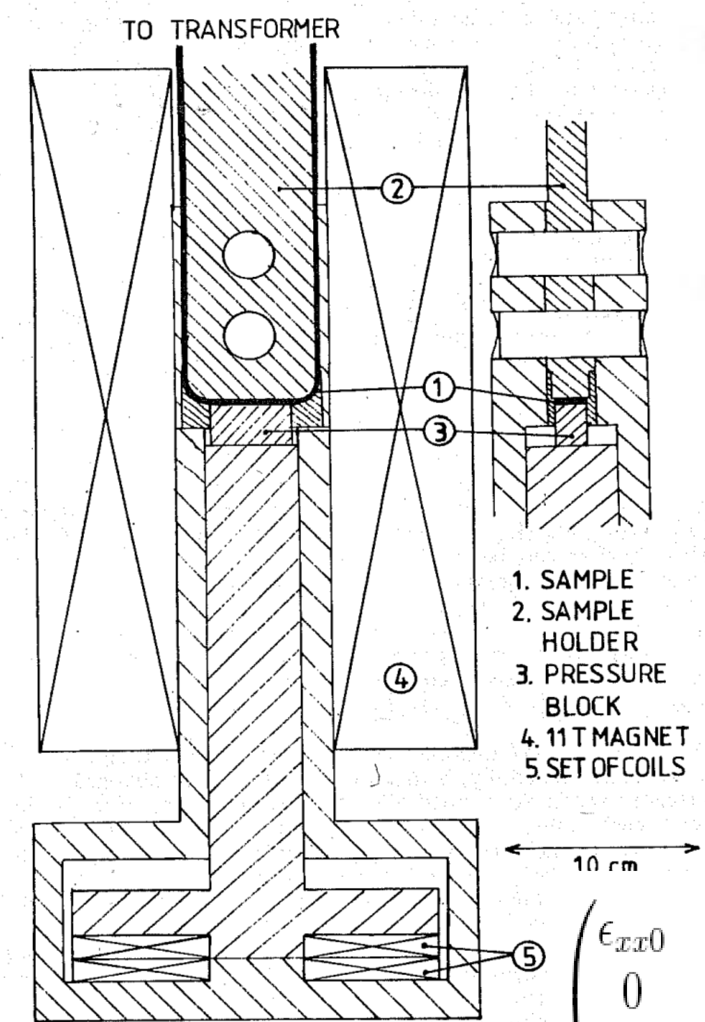


Cable Parameter	Value
Cable thickness	1.3 mm
Cable width	15.09 mm
Cable gap	0.25 mm

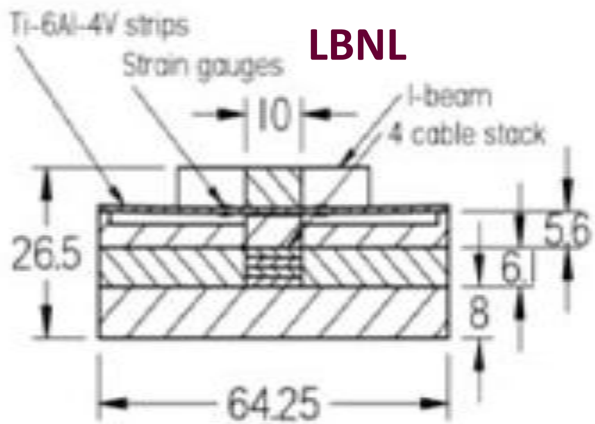
Self-field correction 0.078 T/kA

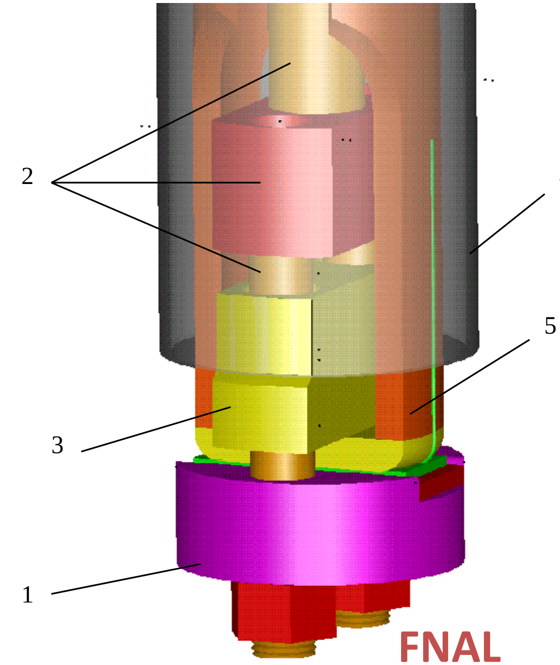
"Commissioning of 14T/16T Rutherford Cable Test Facility with Bifilar Sample and Superconducting Transformer", E. Barzi, Vadim Kashikhin, Vito Lombardo, Allen Rusy, Daniele Turrioni, and Alexander Zlobin, AIP Conf. Proc. 1573, 1192 (2014).

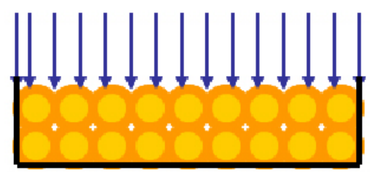
Transverse Pressure - Existing Test Setups



Twente Univ.

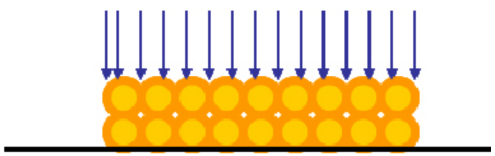






Multi-axial stress state

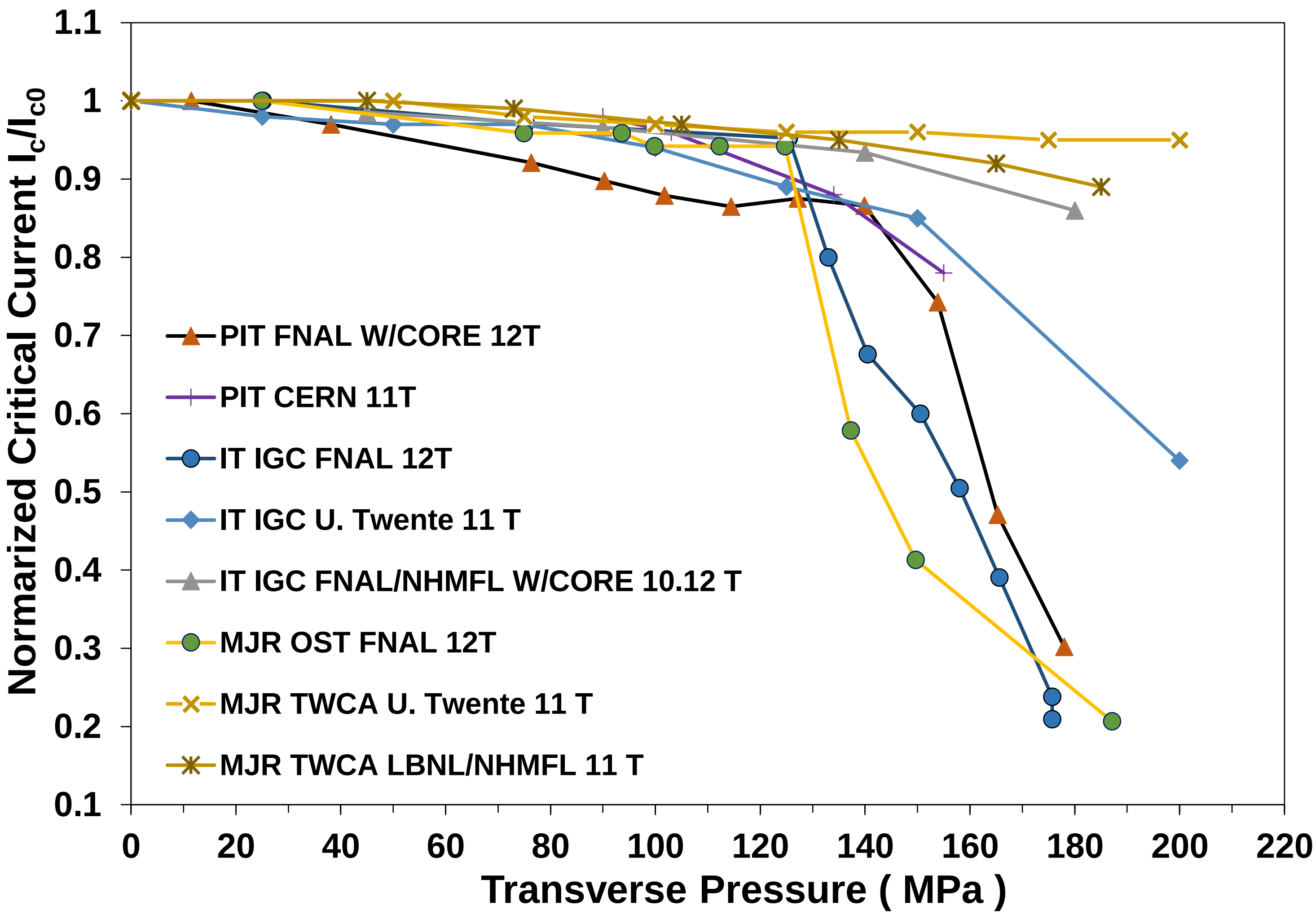
$$\begin{pmatrix} \epsilon_{xx0} & 0 & 0 \\ 0 & (\nu^2 - 1)\frac{p}{E} - \nu\epsilon_{xx0} & 0 \\ 0 & 0 & \nu(1+\nu)\frac{p}{E} - \nu\epsilon_{xx0} \end{pmatrix}$$



Uni-axial stress state

$$\begin{pmatrix} \nu\frac{p}{E} & 0 & 0 \\ 0 & -\frac{p}{E} & 0 \\ 0 & 0 & \nu\frac{p}{E} \end{pmatrix}$$

Example of Results



10 T HFDA Dipole Cables (2002-2005)

Example of cables made for HFDA cable development.

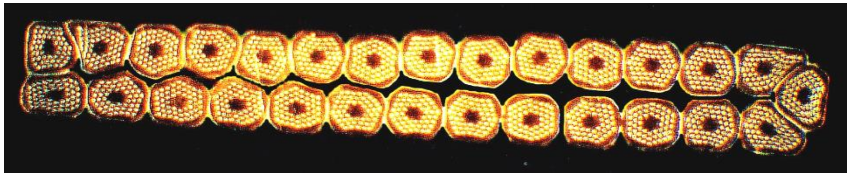


Table II. PIT Cable Parameters.

PIT2	Core	Type	Thickness, mm	*PF*, %
1	Y	R	1.950	84.9
2	Y	KS	1.880	85.6
3	Y	KS	1.860	86.6
4	Y	KS	1.800	89.5
5	Y	KS	1.760	91.5
6	N	R	1.970	83.6
7	N	KS	1.874	84.9
8	N	KS	1.843	86.6
9	N	KS	1.801	88.6
10	N	KS	1.720	93.0

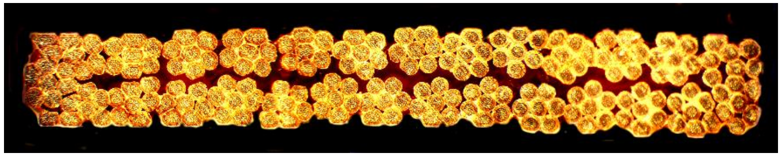


Table 5. Two-stage ITER cable parameters.

Core	Type	Thickness (mm)	PF[a] (%)
N	R	1.970	83.6
N	KS	1.854	86
N	KS	1.833	87
N	KS	1.761	90.6
N	KS	1.721	92.7

[a] Does not include compaction of the 1 mm strand assembly.

Table III. MJR Cable Parameters.

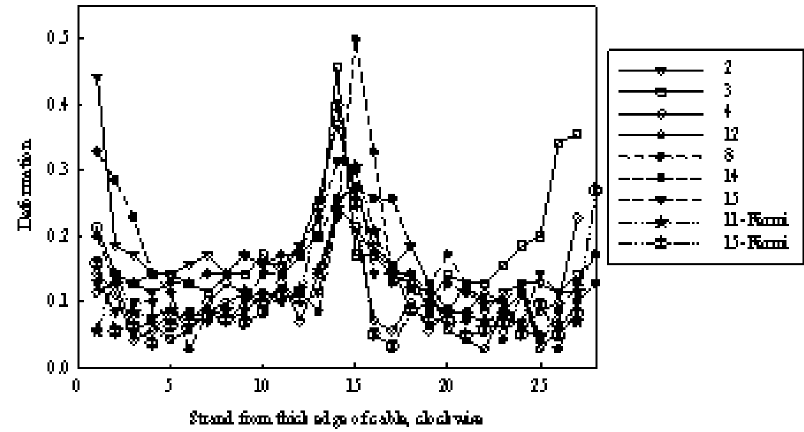
MJR2.	Core	Type	Thickness, mm	*PF*, %
1	Y	R	1.950	84.9
2	Y	KS	1.880	85.6
3	Y	KS	1.860	86.6
4	Y	KS	1.800	89.5
5	Y	KS	1.775	90.7

***"Development and Study of Rutherford-type Cables for High-field Accelerators Magnets at Fermilab"*, E. Barzi et al., Superconductor Science and Technology, special issue, V. 17, No. 5, p. 213 (2004).**

LARP TQ Cables (2006-2009)

Cable ID	No. strands	KS angle, °	Mid-thickness, mm	Average width, mm	PF, %
1	27	0.94	1.182	10.065	90.4
2	“	“	1.223	10.037	87.4
3	“	“	1.259	10.050	84.8
4	“	“	1.293	10.000	83.0
5	28	“	1.182	10.090	93.3
6	“	“	1.224	10.057	90.4
7	“	“	1.262	10.051	87.7
8	“	“	1.295	9.99	86.1
9	27	1.25	1.179	10.093	90.1
10	“	“	1.223	10.033	87.5
11	“	“	1.258	9.973	85.6
12	“	“	1.281	9.985	83.9
13	28	“	1.180	10.103	93.6
14	“	“	1.219	10.100	90.6
15	“	“	1.260	10.063	87.8
16	“	“	1.279	10.00	87.0

Example of cables made for TQ cable development.



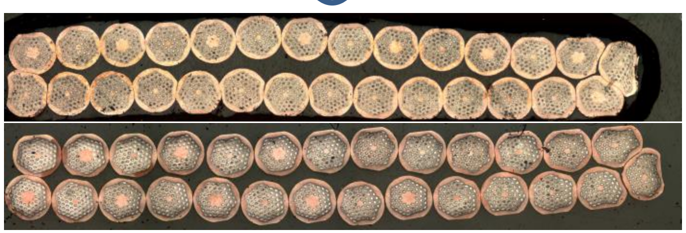


FIGURE 2. Cross section of 28-strand (top) and 27-strand (bottom) mixed cables.

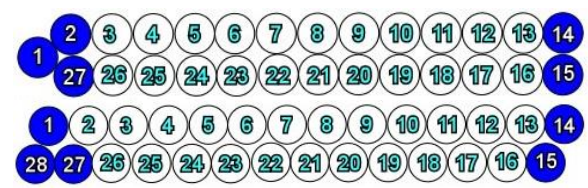


FIGURE 3. Schemes of the strand locations used for 27-strand (top) and 28-strand (bottom) Rutherford cables, where the thick edge is located at the left.

***Effect of Rutherford Cable Parameters on Nb_3Sn Extracted Strand Deformation and Performance*, D. Turrioni et al., IEEE Trans. Appl. Sup., V. 18, No. 2, p. 1114 (2008).**

11 T Dipole Cables (2010-2013)

Example of 40-strand cables with core made for 11 T Cable Development

Cable ID	Step (No.)	RRP® wire design	Width before/after keystoning (mm)	Mid-thickness before/after keystoning (mm)	*PF* before/after keystoning (%)	Annealing step
1	2	150-Ta	14.48/14.66	1.320/1.270	84.8/87.1	No
2	“	“	14.48/14.66	1.320/1.253	84.8/88.3	“
3	“	“	14.48/14.68	1.320/1.230	84.8/89.8	“
4	2	150-Ta	14.57/14.68	1.338/1.270	83.4/86.8	Yes
5	“	“	14.57/14.68	1.338/1.251	83.4/88.4	“
6	“	“	14.57/14.69	1.338/1.232	83.4/89.6	“
7	2	108-Ta	14.59/14.70	1.336/1.270	83.0/86.7	Yes
8	“	“	14.59/14.70	1.336/1.252	83.0/87.9	“
9	“	“	14.59/14.71	1.336/1.230	83.0/89.4	“
10	1	132-Ti	-/ 14.75	-/ 1.271	-/ 85.7	No
11	“	“	-/ 14.71	-/ 1.250	-/ 87.4	“
12	“	“	-/ 14.73	-/ 1.230	-/ 88.8	“

***“Progress in Nb3Sn RRP Strand Studies and Rutherford Cable Development at FNAL”,* E. Barzi, D. Turrioni and A. V. Zlobin, IEEE Trans. Appl. Sup., article #6000808, V. 24, No. 3 (2014).**

Cables used for 1-pass Commissioning (2012)

	R&D_PC_01	R&D_CF_01_13	DM_CF_08_01_01	Cu practice	R&D_CF_03_13	R&D_CF_02_13	R&D_CF_04_13
Date	02.28.13	03.04.13	03.12.13	03.26.13	08.30.13	09.09.13	09.11.13
Length, m	20	10	216	10	50	20	600
Finished length, m		1.9/1.85/3.45	204.3	7.65	46.14	12	583.6
Compostion	**Cu**	**Nb3Sn**	**Nb3Sn**	**Cu**	**Cu**	**Nb3Sn**	**Cu**
Billet	A101	11444/14841-6	11444	A101	A101	multiple	A101
Avg. strand dia., mm	0.699	0.701	0.701	0.699	0.7	0.702	0.7
Core width, mm	11.00/7.00	7	9.52	11	9.52 & 11.00	11	11
Mandrel ID	482012B	482012B	482012B	482012B	482012B	482012B	482012B
Side roller, mm	5.52	5.52	5.52	5.52	5.52	5.52	5.52
Turkhead postion, mm	41.52	41.52	41.52	41.51	41.53	42.95	41.53
Strand tension, lbs	4.5	4.5	4.5	4.5	4.5	4.5	4.5
Spindle current, uA	185	185	185	185	185	185	185
Avg. width, mm	14.76/14.77	14.713	14.73	14.7	14.68/14.71/14.69/14.71	14.74/14.74/14.75	14.71
Avg. thickness, mm	1.218/1.227	1.23/1.25/1.27	1.251	1.251	1.250/1.249/1.251/1.249	1.240/1.213/1.289	1.25
Packing factor, %	89.4/89.0	88.8/87.4/85.7	8780.00%	8790.00%	88.1/88.4/88.7/88.9	89.5/91.4/85.9	88.7
Avg. lay angle, deg	15/15.5	15.6/15.8/15.8d	15.6	14.3	15.5/16.5/17/17.5	17	16.8
Avg. Tension, %		99	91	112	111	140/181/166	122

200m+ Superconducting cable with one single billet

Relative Rotation Experiment

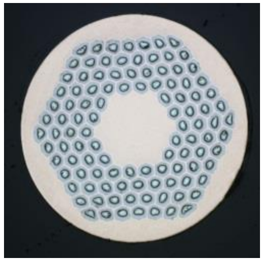
SC Cable with Multiple Billets

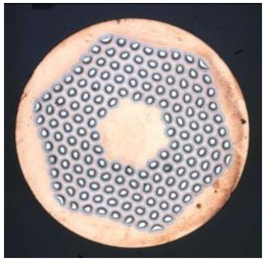
15 T Demonstrator Cables (2014 to date)

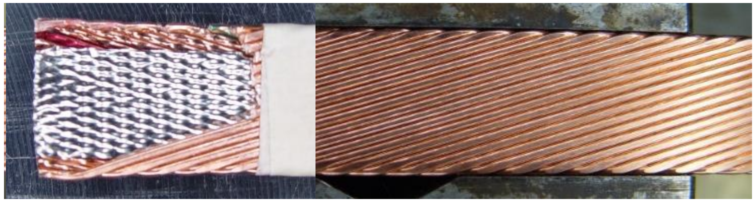
- **Effect of cable Packing Factor (PF) on I_c degradation and RRR**
- **Effect of pre-treating the wires before cabling**
- **Effect of magnetic field on RRR**

CABLES FOR DEVELOPMENT OF 15 T DIPOLE

Cable ID	RRP® wire design	Width (mm)	Mid-thickness (mm)	Lay angle, (deg)	*PF* (%)
1	RRP1, RRP2	14.84	1.804	16	86.7
2	"	14.87	1.759	16	88.7
3	"	14.82	1.737	16	90.2
4	"	14.85	1.707	16	91.6
5	"	14.89	1.689	16	92.3
6	RRP3	14.89	1.835	17.5	85.4
7	"	14.89	1.812	17.5	86.5
8	"	14.93	1.786	17.5	87.6
9	"	14.94	1.762	17.5	88.7
10	"	14.94	1.736	17.2	89.9
11	"	14.94	1.710	17.4	91.4
12	"	14.94	1.685	17.6	92.8
13	RRP3, pre-treated	14.90	1.836	16.9	85.0
14	"	14.89	1.813	17.0	86.2
15	"	14.92	1.787	17.0	87.3
16	"	14.91	1.766	17.0	88.4
17	"	14.91	1.734	17.3	90.2
18	"	14.94	1.710	17.3	91.3
19	"	14.90	1.684	17.0	92.8







***Nb_3Sn RRP® Strand and Rutherford Cable Development for a 15 T Dipole Demonstrator*, E. Barzi, N. Andreev, P. Li, D. Turrioni, and A.V. Zlobin, IEEE Transactions on Applied Superconductivity, Vol. 26, Issue 4, Art. # 4804305.**

Cable Production FY11-FY16

Coil ID	Cable N x D	Billets ID	Strand Type	Cable length	Cable geometry	Core width	Cable fabrication
MBH02, MBH03	40 x 0.7 mm	12292, 12319, 12521-22, 13062-63, 13090	108/127 (Ta)	414 m	1.251±0.001 x 14.71±0.01 mm^2, 15.0 deg	None	Jul. 2011, 2-pass w/intermediate anneal
MBH05, MBH07	40 x 0.7 mm	13538, 13613	150/169 (Ta)	120 m 230 m	1.251±0.002 x 14.69±0.01 mm^2, 15.0 deg	11.0 mm	Sep. 2011, 2-pass w/intermediate anneal
MBH08	40 x 0.7 mm	14144, 14145, 14194, 14195, 9772	108/127 (Ta), 114/127	138 m	1.252±0.004 x 14.71±0.01 mm^2, 14.0 deg	11.7 mm	Nov. 2012 1-pass
MBH09	40 x 0.7 mm	14144, 14145, 14194, 14195, 14700	108/127 (Ta)	180 m	1.249±0.002 x 14.70±0.01 mm^2, 14.8 deg	11.0 mm	Nov. 2012 1-pass
MBH10, MBH11	40 x 0.7 mm	14144, 14145, 14194, 14195, 14700	108/127 (Ta)	220 m	1.245 x 14.72 mm^2, 15.0 deg	11.0 mm	Nov. 2012 2-pass w/intermediate anneal
Practice coils	40 x 0.7 mm	11444	132/169 (Ti)	216 m	1.251 x 14.73 mm^2, 15.6 deg	9.5 mm	Mar. 2013 1-pass
	40 x 0.7 mm	A101	Hard Cu	600 m	1.250 x 14.71 mm^2, 16.8 deg	11.0 mm	Oct. 2013 1-pass
15 T Dipole Outer Layer	40 x 0.7 mm	15043, 15044, 15045, 15244, 15245, 15290	108/127 (Ti)	374 m	1.251±0.001 x 14.71±0.01 mm^2, 16.8 deg	11.0 mm	Oct. 2013 1-pass
15 T Dipole Inner Layer	28 x 1 mm	16638, 16639, 16640	150/169 (Ti)	420 m	1.803±0.002 x 14.79±0.02 mm^2, 15.5 deg	11.0 mm	Dec 2015 1-pass

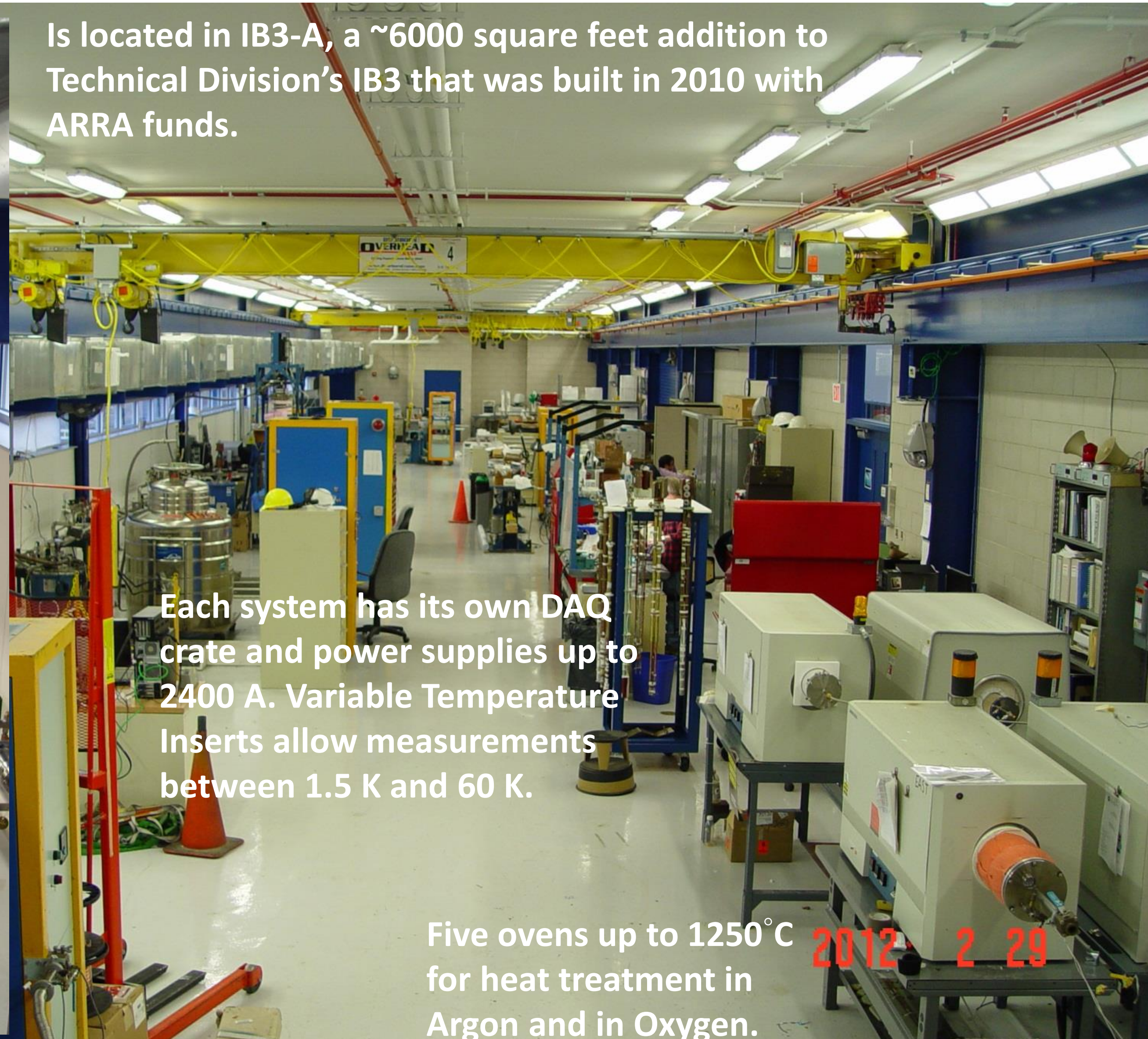
Appendices

Superconductor Equipment List at FNAL, IB3A

- Teslatron 1 (T1) Cryostat with 15T/17T 64 mm cold aperture solenoid, 1875 A Power Supply w/ 49 mm Variable Temperature Insert (VTI) for testing between 1.5 K to 300 K
- Teslatron 2 (T2) Cryostat with 14T/16T and 77 mm cold aperture solenoid, 2000 A PS w/VTI
- Teslatron 3 (T3) Cryostat with 8.5T/10T and 147 mm cold aperture solenoid, 2400 A PS
- Telslatron 4 (T4) Cryostat with 253 mm neck, 2400 A PS
- Low temperature loader for cryogenic strain gauge calibration
- 4 tube furnaces 6’’ diameter for heat treatment in Argon and Oxygen to 1500°C
- 2 m long furnace up to 1250°C for heat treatment in air and in argon
- Metrology well calibrator for thermocouples calibration up to 700°C
- Motorized flat-rolling system for wires
- Probes and sample holders for SC strand critical current tests up to 2000 A in T1 and T2
- Devoted probes to test RRR of up to 6 wire samples in T1,T2 and T3
- Sample holders to measure angular dependence of current with field for HTS wires in T1 and T2
- Balanced coil magnetometer to measure magnetization in T1 and T2
- Device to test critical current sensitivity of impregnated cables to uniaxial transverse pressure in T2
- Walters’ spring-type device for tensile/compressive strain sensitivity studies of critical current density in T1
- SC transformer for Rutherford cable tests and splice studies up to 28 kA in self-field in T1 and T2
- 14T/16T Rutherford cable test facility for cable tests up to 30 kA in T2
- Modular Insert Test fixture for testing HTS YBCO pancake coils in T2
- Hall probe system for magnetic measurements in T4, eg shielding capabilities of bulk MgB_2 tubes
- Instrons for mechanical properties
- Optical and electron microscopes
- Respooler and 42-spool cabling machine with turkheads for 1-step and 2-step cables

IB3A Superconducting R&D Lab

Four magnetic cryostats with up to 15T/17 T background field, and with cold apertures between 64 mm and 147 mm are connected to new vent and vacuum systems.

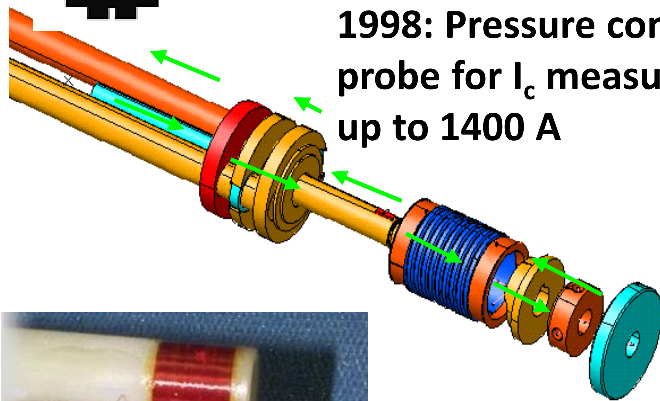


Is located in IB3-A, a ~6000 square feet addition to Technical Division's IB3 that was built in 2010 with ARRA funds.

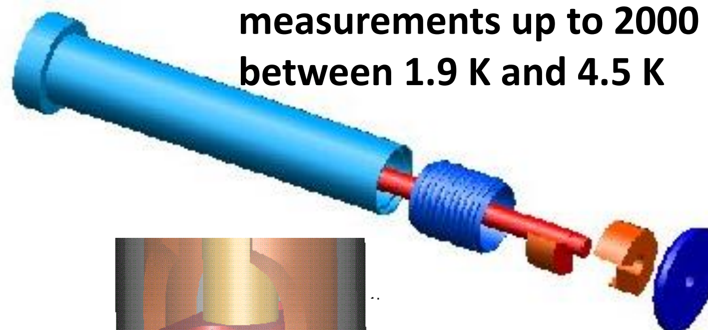
Each system has its own DAQ crate and power supplies up to 2400 A. Variable Temperature Inserts allow measurements between 1.5 K and 60 K.

Five ovens up to 1250°C for heat treatment in Argon and in Oxygen.

Experimental Setups

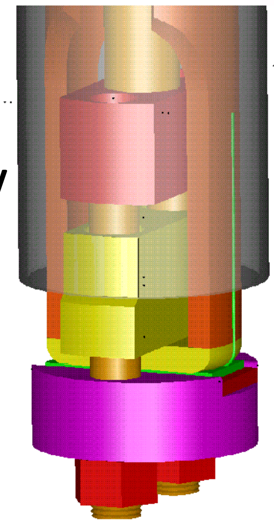


1998: Pressure contact probe for I_c measurements up to 1400 A

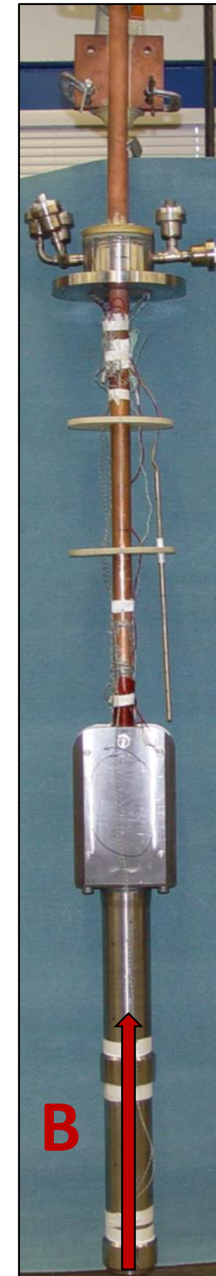


2003-2009: Five low resistance probes for stable current measurements up to 2000 A between 1.9 K and 4.5 K

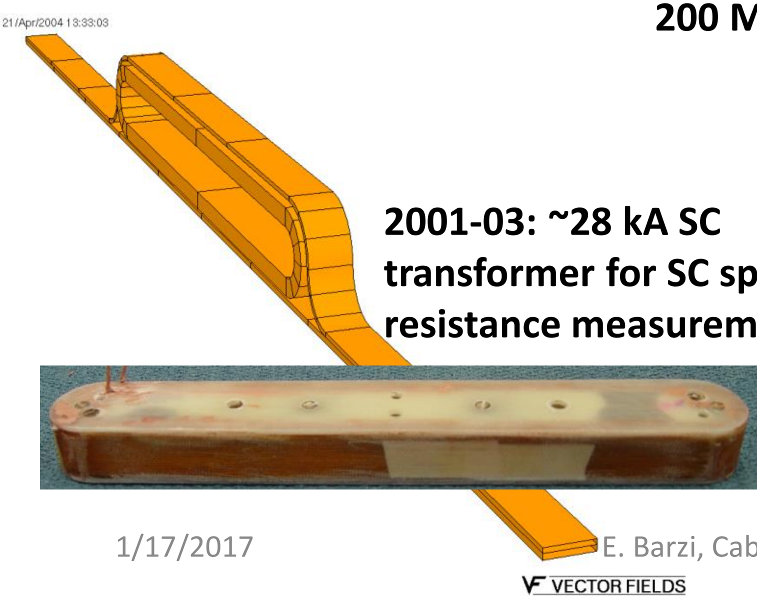
1999: Balanced coil magnetometer for magnetization measurements



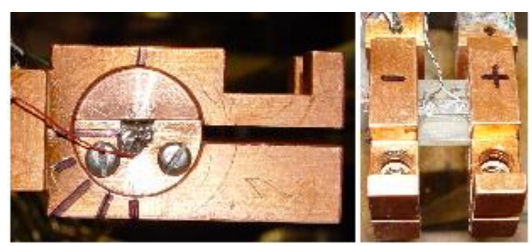
2001: Device to test I_c sensitivity to uniaxial transverse pressure up to 200 MPa



2009-13: SC transformer for cable tests in fields up to 14T/16T and ~30 kA

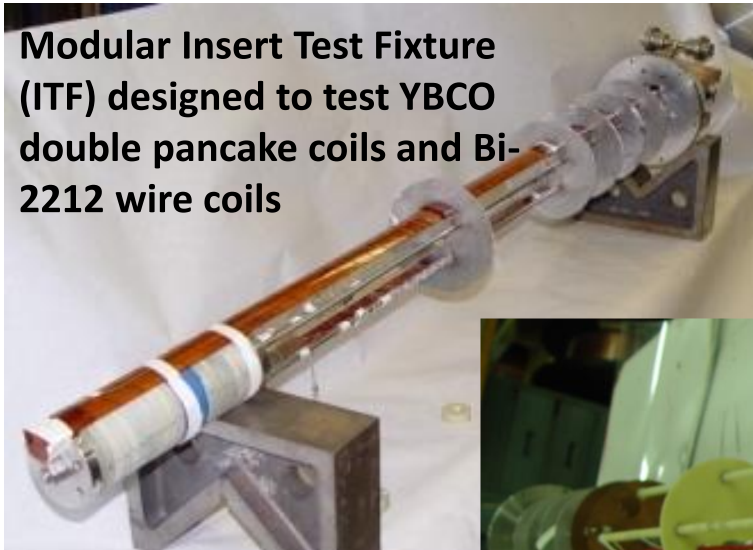


2001-03: ~28 kA SC transformer for SC splice resistance measurements

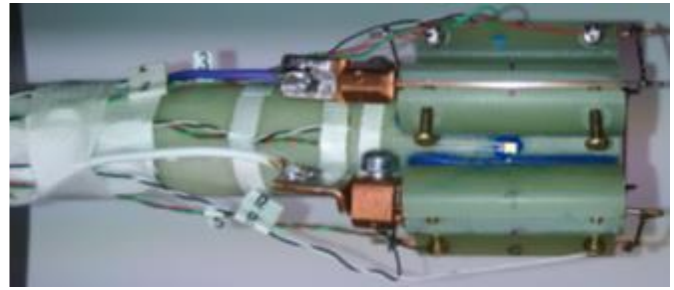


2007: Probe to measure I_c dependence on field orientation for anisotropic HTS wires.

Experimental Setups (cont.)



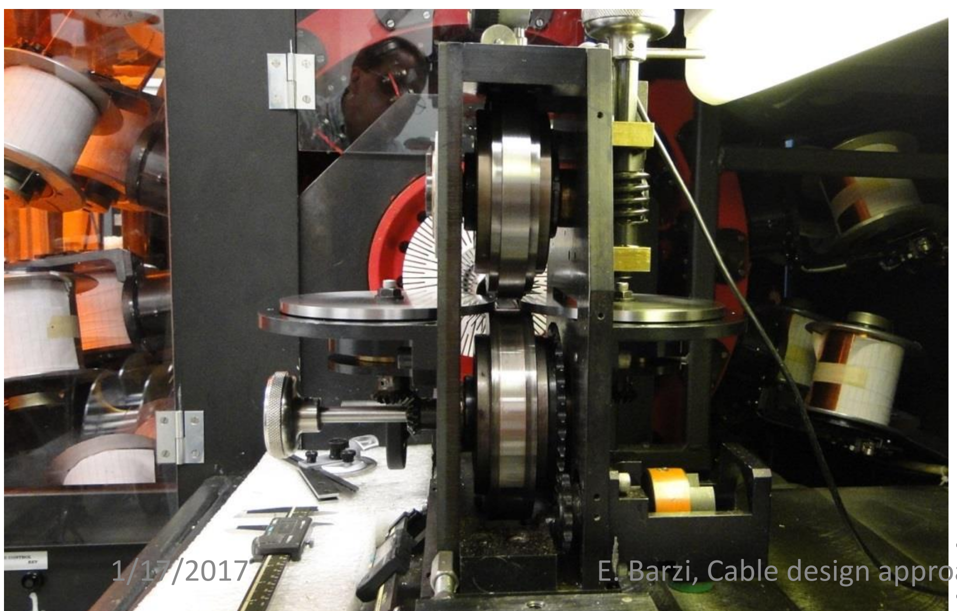
Modular Insert Test Fixture (ITF) designed to test YBCO double pancake coils and Bi-2212 wire coils



New RRR probe for wire and bulk samples

New Hall probe system to measure shielding of bulk MgB_2 tubes

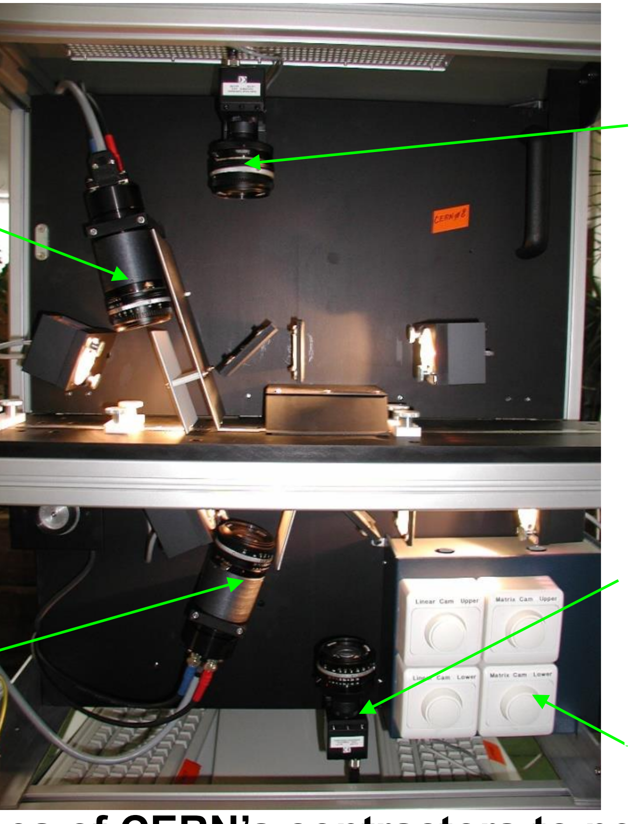
Walters' Spring probe for strain sensitivity studies of I_c in SC wires



New keystoned turkhead for Rutherford cable fabrication in 1 step

CERN Cable Inspection System

- Was commissioned and can only be used offline due to large amount of spurious signals.

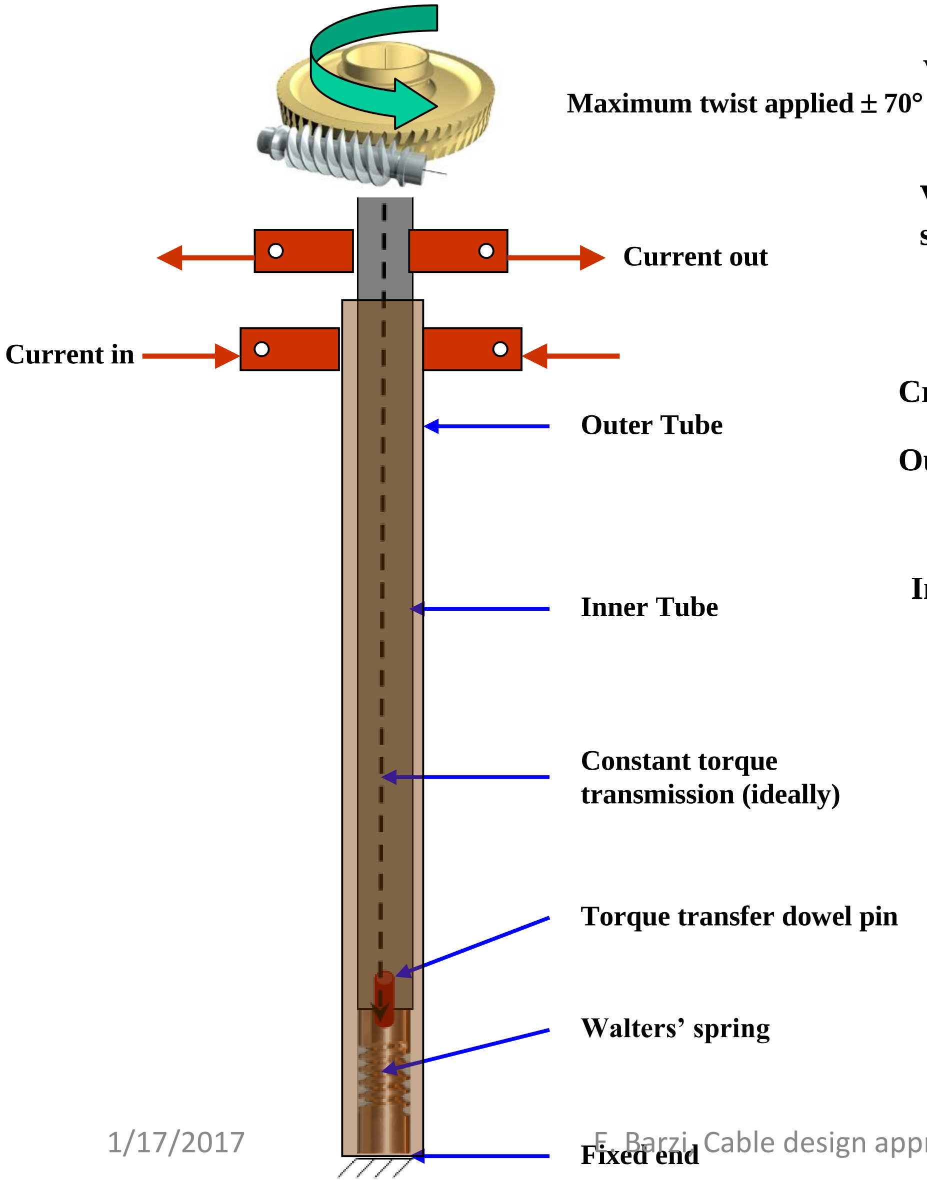


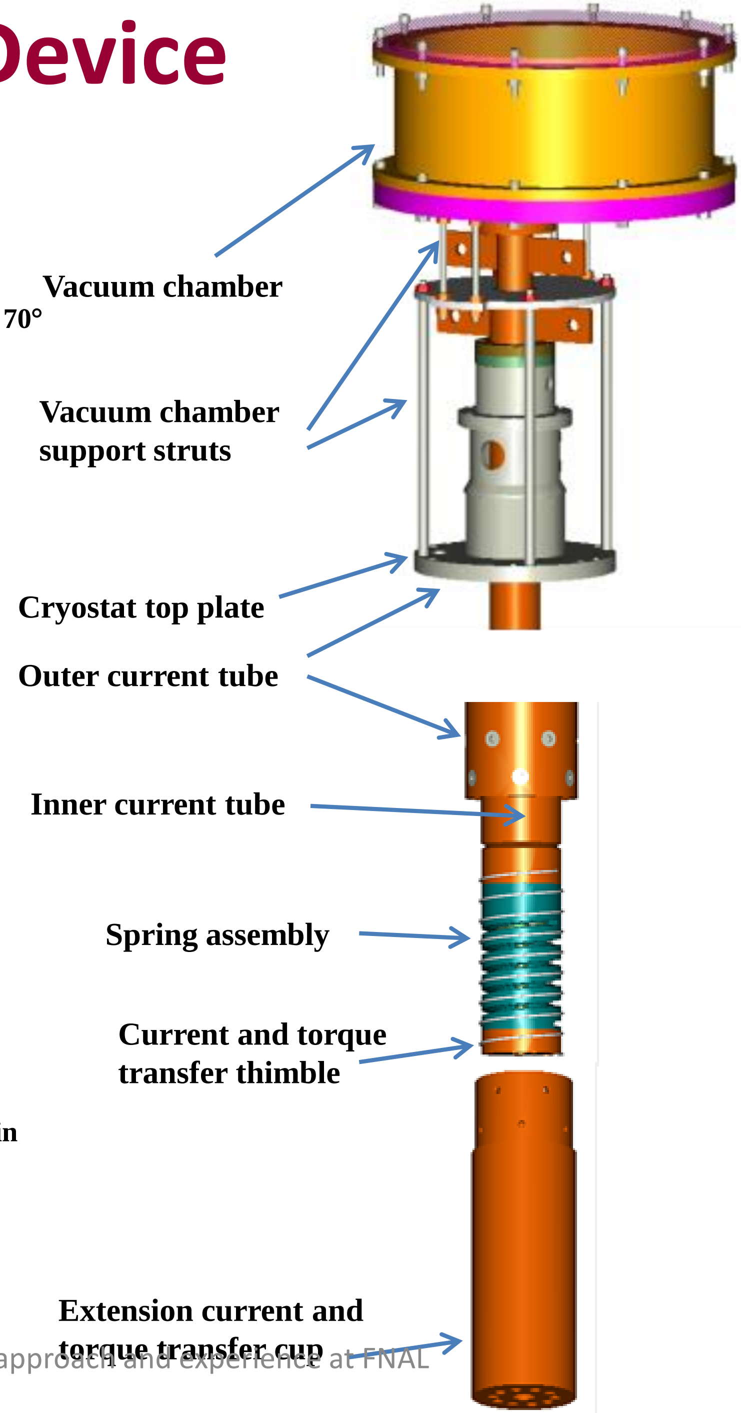
✓These systems were installed in the cabling lines of CERN's contractors to perform a continuous inspection of the cable in order to detect and localize defects.
✓Defects are classified as minor or major, position marks and cold welds are detected and localized.
✓A sound alarm as well as a light signal (green, orange, red) are activated according to the different types of detection, a status report of the cable run is issued.

Examples of Collaboration with CERN

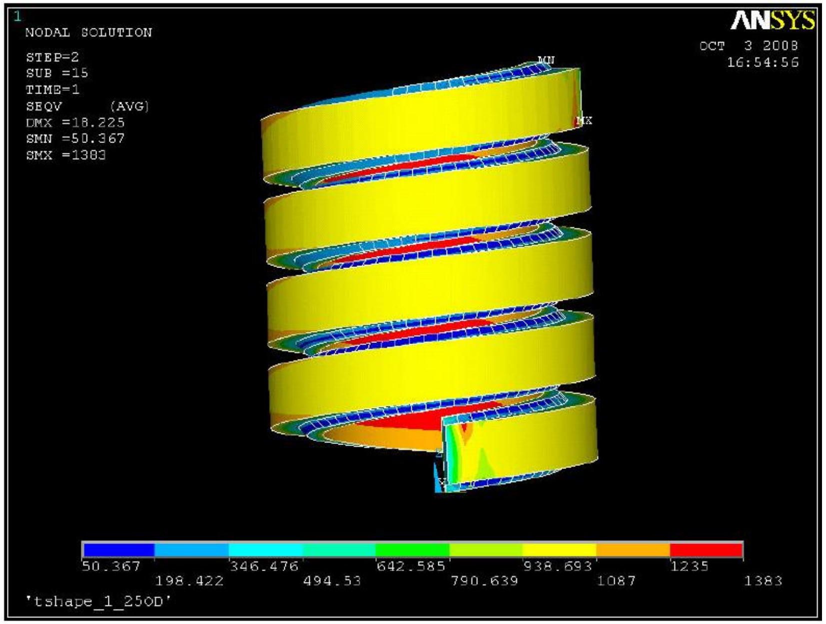
- **The Spec v.2 for the cable were discussed and agreed upon during E. Barzi's visit at CERN in March 2012**
- **CERN produced the cable for the spare coil (MBH04) for the 1-1 demonstrator**
- **Traveler and reporting templates for cable production were discussed and exchanged during Barzi's visit**
- **To prepare for automated quality control, CERN shipped one of their Inspection Systems following Dan Turrioni's prior visit**

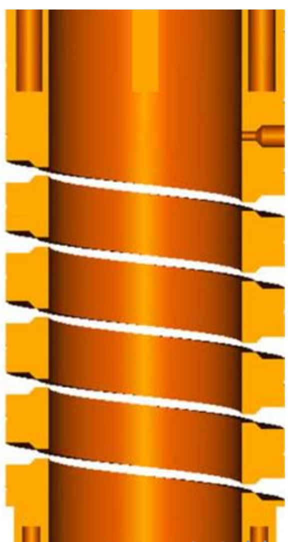
Walters' Spring Device

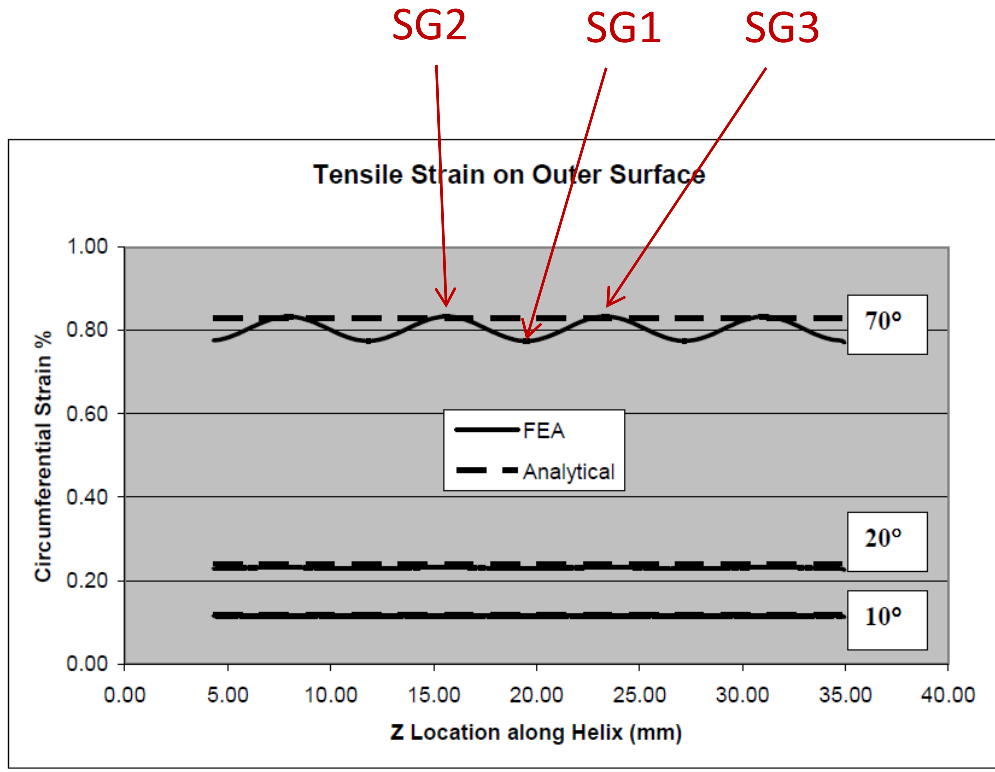




Spring Models

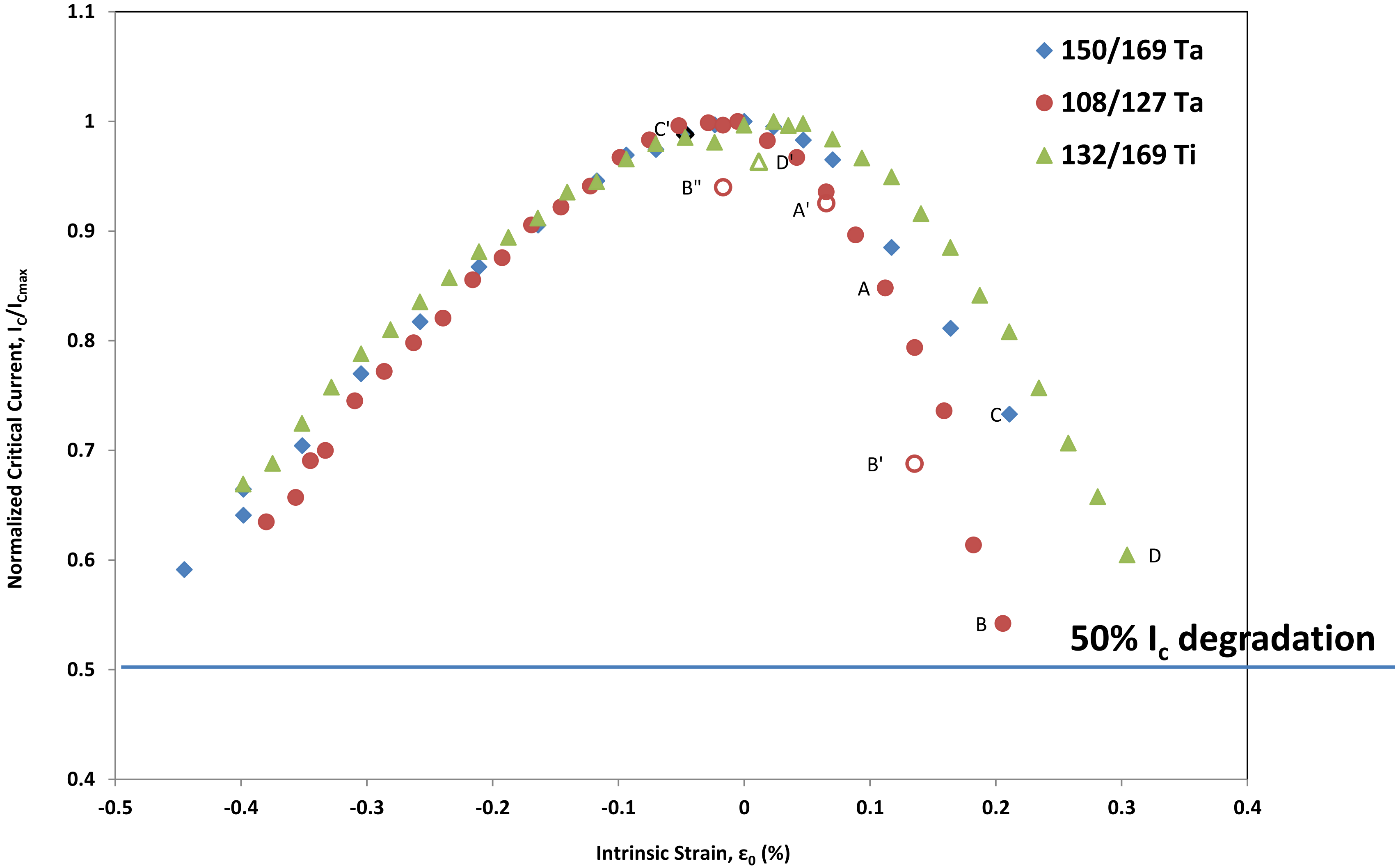






Two spring materials were used, Cu-plated Ti-6Al-4V and CuBe.

Strain Effects: Ta-alloyed vs. Ti-doped RRP Wires



Normalized I_c(4.2 K, 15 T) as function of longitudinal intrinsic strain over channel CH1 for 0.7 mm samples of Ta-alloyed 108/127 RRP®, Ta-alloyed 150/169 RRP® and Ti-doped 132/169 RRP®.

Cable Expansion – Tooling Design

- **The coil dimensions in the winding and curing tooling are determined by the unreacted cable cross section, whereas the coil dimensions in the reaction and impregnation tooling are based on the reacted cable cross section.**
- **Experimental data indicate that the Nb_3Sn cable cross section expands anisotropically during reaction. The change in dimensions before and after reaction was measured for five keystoned nominal cables which were stacked on the flat face in a stainless steel straight fixture 1.22 m long. The cables were placed within a groove with enough room for the cables to expand freely in all three directions. Mica layers 0.15 mm thick were placed between the cables.**
  - **The average width expansion was 2.6% ± 0.2%**
  - **The average mid-thickness expansion was 3.9% ± 0.5%, and**
  - **The average length decrease was 0.3%.**

See also N. Andreev et al., "Volume expansion of Nb_3Sn strands and cables during heat treatment", Advances in Cryogenic Engineering, V. 48, AIP, V. 614, pp. 941-948 (2002).

See also E. Barzi et al., "Development and Fabrication of Nb_3Sn Rutherford Cable for the 11 T DS Dipole Demonstration Model", IEEE Trans. Appl. Sup., V. 22, No. 3, pp. 6000805 (2012).