FCC WEEK 2018 AMSTERDAM, The Netherlands

Update on the potential of Bi-2212 for high field magnet use

D.C. Larbalestier

With major collaborators Eric Hellstrom, Jianyi Jiang, Fumitake Kametani and Ulf Trociewitz at the NHMFL, Tengming Shen at LBNL, multiple PhD students and staff and many industrial partners noted on the next slide

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2212 conductor development has been a Collaboratorium

At ASC-NHMFL-FSU

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An integrated effort by DOE-OHEP, SBIR program, NSF through NHMFL and some key early support by CERN through EUCARD2 – and now USMDP

Our external collaborators

Tengming Shen (LBNL) Yibing Huang and Hanping Miao (B-OST) Marvis White, Riley Nesbit, Aixia Xu and Andrew Hunt (nGimat) Alex Otto (SMS) Suvankar Sengupta and Rao Revur (MetaMateria)



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Outline of the talk

- Conductor
 - Good powder
 - Good wires
 - Twisted with low hysteretic loss made in single pieces with 1-2 km length at 1 mm and 0.8 mm diameter
- Coils
 - Reliable HT under 50 bar is now routine
 - Double insulation scheme valid on 1 km scale
 - We can reinforce conductor in winding pack to support >300 MPa in tension – higher stress at 0.4% strain in view
 - A new reaction chamber (25 cm dia./1 m long) and magnet test bed (14 T/160 mm bore) is under active MDP discussion

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Key messages

- No one is going to use any HTS conductor if they can use Nb-Ti or Nb₃Sn.....
- All HTS conductors are 7-15 times the (volumetric cost) of Nb₃Sn.
- High Field or High Temperature use are key

Magnet builders much prefer round, twisted, isotropic conductors with high conductivity normal metal around the filaments

This is exactly what Bi-2212 offers – in many architectures with J_c well exceeding Nb₃Sn from about 12 T up



Two small US companies now making powder

- MetaMateria
 - Use co-precipitation
- nGimat
 - Use spray combustion to form 2212
- Replicating the Nexans 521 composition
- New 2212 powders are better than the best of Nexans*
 - No need for grinding agglomerated bulks

Particle size and uniformity better than Nexans Important contribution of CERN in context of EUCARD-2 for enabling Nexans final powder production from which we learned much due to care of Mark Rikel in its manufacture

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Nexans was the benchmark producer for more than 10 yrs



Note for FCC magnet builders: J_c far exceeds the FCC specification (~1850 A/mm² at 15 T) and with only 20% superconductor cross-section, very high conductivity Ag without any diffusion barrier that can break during cabling and then degrade the RRR

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AGI AR

Recent nGimat and MetaMateria powders established a new benchmark (2017) in standard B-OST wires

Powder LXB-43

Powder LXB-52

IAGI AB



New level of phase and particle size control with "simpler" and cheaper processes

New record Jc for 0.8 mm wire from nGimat LXB 52 70% increase in Jc over the last and best Nexans lot 87

Reacted state sub-bundles (Some interfilament connections but with low hysteretic loss)



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Round wire Jc goodness plot



 $J_c(H)$ falls off only slowly because $H_{irr} >> 50$ T: J_c (20T) is 83% and J_c (30T) 72% of J_c (15 T)

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High Field Data shows excellent J_c(H) scaling out to at least 31 T – connectivity is the dominant multiplier for Jc(H)



Viewed globally, wires of last few years with different powders have large range of Jc Normalized Jc(H) relations are all very similar F_{pmax} does not peak at 31 T and 4 K

Kramer vs Field - pmm170123-3



Michael Brown (PhD 2018)

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Twisting reduces coupling losses and does not degrade Jc



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50 bar Over Pressure (OP) removes filament size dependent properties (1.5-1.0 mm wire dia.) – and widens the HT window



Jiang et al., IEEE Trans. Appl. Supercond., 27, 4, 6400104 (2017))

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Getting the conductor into magnets

- Must react coil at almost 900C, not just short samples – and at 20-100 bar overpressure (OP) – we use 50 bar now (1 bar O₂, balance Ar), almost exclusively
- Coil insulation must withstand reaction after winding
- Strengthening methods must be available for low E (70 GPa) and low $\sigma_{0.2}$ (~100 MPa) and be applicable to coil manufacture

Overpressure increases Jc by 5-8 times and prevents internal pressure leakage





DCL et al, Nature Mat 2014

Bi-2212 Conductor Strengthening is mimicking 2223

Low aspect ratio applied to preserve . electro-magnetic isotropy of wire

Alex Otto (SMS) and Michael Brown (FSU)



Shown here is a wire bonded with reinforcement tape made by Solid Materials Solutions (SMS, Alex Otto)

Stress (MPa) 150 100

425 MPa at 0.4% strain versus 118 MPa for 2212/Ag

~3.5 fold benefit with 33% strip area (similar to SEI 2223 NX).

Work on reinforced conductor in coils is ongoing – as also is round wire strengthening

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FSU Measurements on SMS tapes given **OPHT** at FSU



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AGI AB

Insulation for 2212: hybrid TiO₂ and mullite fiber

- Dip coating process with TiO₂ particles dispersed in a polymer
- Polymer burns off leaving strong ceramic layer



- >1 km lengths now being coated reliably
- Added alumino-silicate braid to improve stand-off and winding pack integrity



• Tests at LBNL of their coated and braided race-track coils have also shown higher leak resistance along with an improvement of transport properties

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2212 test coils: thick (pups) and large diameter (Riky) for high stress



- We build Coils of various sizes from small bobbins to fully instrumented larger coils for in-field testing applying analysis lead design
- Models coils are confidence builders
 for larger high-field coils like Platypus
 and beyond (testing new concepts,
 models, manufacturing procedures)

About 1 km of conductor each!

Youngjae Kim, Ernesto Bosque and Ulf Trociewitz



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Goals: Understand and control performance limits of our 2212 coils

- Model coils with conductor resolution
- **Compare with experiments**



Riky concept: test coils with large bore size to generate high hoop stresses, TiO2 and braid insulated wire, varying reinforcement



Pup concept: test coils with same ID and OD as Platypus to allow observation of strain gradients across winding pack, TiO2 and braid insulated wire, varying reinforcement

Ernesto Bosque, Youngjae Kim, and Ulf Trociewitz

RIKY 3 test coil

- FEA modeling is predicting coil performance well: 348 A predicted for onset of damage (Bjoerstad data confirmed by us (Michael Brown)
- The first trip was observed at 350 A compared to expected of 348 A!
- Very clearly not an *I_c* transition but rather a strain induced trip
- In no-reinforced condition the outer layer would have experienced a stress of ~300 MPa: reinforcement is effective
- Showed saturation of *I_c* retention on subsequent quenches
- Below onset of thermal runaway the coil could be load-cycled many times

Youngjae Kim, Ernesto Bosque and Ulf Trociewitz



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Predicted peak strain expected for given Riky-3 operating currents are shown as blue line plotted against I_c/I_{c0} retention curve based on data by C. Scheuerlein*, CERN

*R. Bjoerstad, C. Scheuerlein, M. Rikel *et al.*, Supercond. Sci. Technol. 28 (2015) 062002

A new HTS test bed

14 T Magnet by Cryogenic LTD to be commissioned soon at ASC:

- Magnet bore 161 mm
- 128 ppm homogeneity (1 cm DSV) without compensators or shims
- Is ideal test bed to explore performance limits of HTS inserts for improving performance predictions
- Magnet provides sufficient space to run 2212, 2223 or REBCO coils up to 30 T

300 mm

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Lamar English, Ernesto Bosque, Eric Hellstrom and Ulf Trociewitz

Our High Pressure Furnace is the Work Horse for Bi-2212 Coil Heat Treatment

- First-of-its-kind pressurized 6-zone furnace built by Deltech
- Currently largest OP furnace available for Bi-2212 heat treatment
- Design parameters: 900 °C, 100 atm total pressure, 500 mm hot zone – currently use 50 atm and the hot zone is ~430 mm (130 mm dia.)
- This furnace required extensive in-house engineering to make it a robust, reliable equipment
- Successful heat treatment of many coils

Lamar English, Ernesto Bosque, Eric Hellstrom and Ulf Trociewitz



Outer wall dia: 324 mm Working Hot Zone dia: 130 mm Working Hot Zone height:



²Hot Zone is Very Uniform Even with Large Thermal Mass – Platypus-II Dummy Coil



Dummy coil with three 18 layer, 3 turn test sections to verify calibration and OPHT procedure

Stack of metal rings to simulated thermal mass of Platypus –II coil

Thermocouples monitoring locations on dummy

Ernesto Bosque



Zone1.5 – 707 A, 988 A/mm²

Zone2.5 – 697 A, 973 A/mm²

Zone3.0 – 697 A, 973 A/mm²

Placement and *I_c J_c* values of short samples

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OPHT Yields Uniform Transport from Top to Bottom and from Inside to Outside



Four important outcomes: Delta

Deltech Furnace Zone #

- Coils performed consistently throughout the dummy stack
- No oxygen deficiency in inner layers
- Bottom windings survived compressive force of (simulated) winding pack
- We can handle the thermal mass and weight of Platypus-II



Zone 1.5 – 707 A, 988 A/mm²

Zone 2.5 – 697 A, 973 A/mm²

Zone 3.0 – 697 A, 973 A/mm²

Placement and I_c ,J_c values of short samples

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LBNL HTS (2212) subscale magnet program topped with new RC-05 results

RC5 – 3.4 T, J_{cable} = 740 A/mm², J_{wire} = 940 A/mm². Made possible by OPHT at FSU, wire by Bruker OST, and powder by nGimat.



Subscale coils allow fast-turnaround test of cable and magnet-relevant technologies.

LBNL 17-strand Rutherford cable







LBNL RC-1,2,3,5 in ESU OP furnace



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RC5 – E-J characteristics defined with a stair-case I(t) run. Many resistive, easy to detect signals revealed before the quench (global superconducting transition driven by continuous joule heating)



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The global superconducting transition - Multiple turns turning normal makes possible easy quench detection.



Plans for a Larger OP Furnace

• Current furnace:

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- Working Hot Zone height: 430 mm
- Working Hot Zone dia: 130 mm
- Due to a demand of heat treating larger coils (race-track, CCT coils with LBNL, and solenoids) we started planning for a bigger OP furnace
- Pressure range will be 50 bar
- New furnace specs:
 - 1 m working hot zone height (900°C)
 - 266 mm working dia.
- Major components to be sourced through commercial suppliers, assembly at the Lab, Labview controlled



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Lamar English, Ernesto Bosque, Eric Hellstrom and Ulf Trociewitz

Present status: 2212

- The conductor technology is mature at present scale
 - Single 10 kg piece lengths: 2.4 km at 0.8 mm, ~1 km at 1 mm
 - Twisted, multifilament, isotropic, low loss conductor with high RRR (> 100) and no need for diffusion barrier
- Insulation technology for single wires is good
- Reaction under 50 bar to 13 cm dia. x 40 cm length
- Strain control at ~300 MPa demonstrated in coils with strengthened wires at >400 MPa
- We have successfully replaced the classical powder producer Nexans with two new suppliers, nGimat and MetaMateria

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Thank You!

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