Review of 'cos-theta' HTS accelerator magnets

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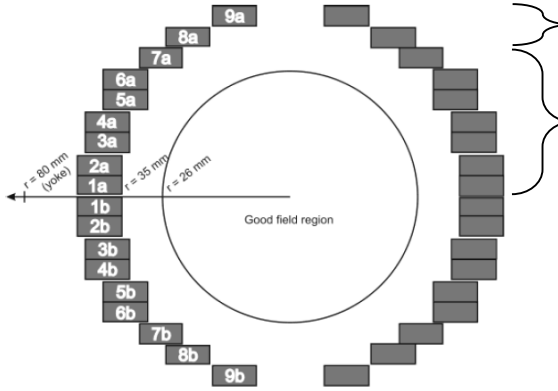
Danfysik-SuperPower-Aarhus University (2012)

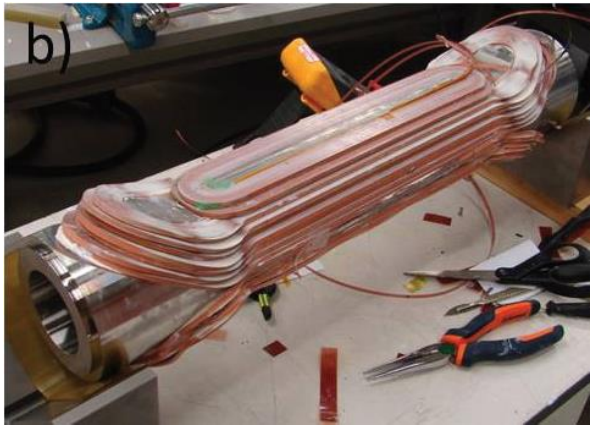
- Cos-theta-like elliptic distribution



2 racetrack coils x 2

7 saddle coils x 2

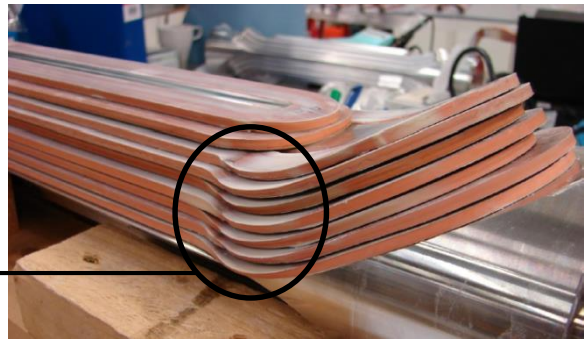
magnetic length: 250 mm
aperture diameter: 70 mm

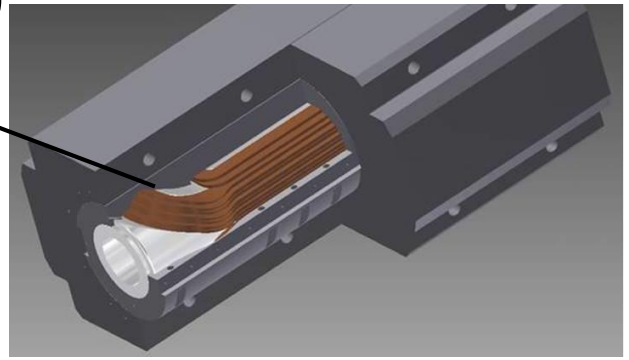


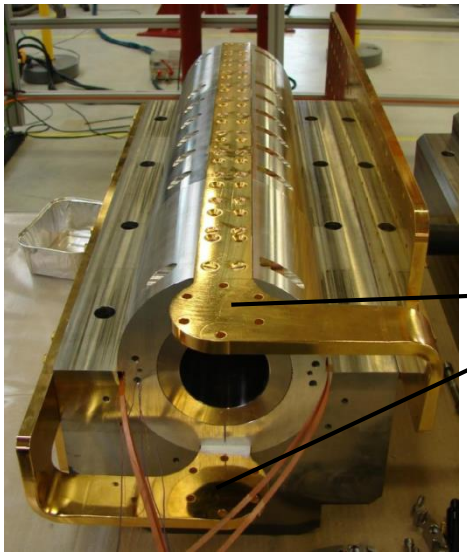
- Tapes:
  - Length: 2.5 km (18 pieces of tapes from 93 m to 172 m)
  - Width: 4 mm
  - Thickness: 50 µm Hastelloy + 1.5 µm YBCO + 2 x 20 µm copper
    + 2 x 25 µm epoxy-based insulation layer with heat conducting filler
  - Current: I_c > 115 A (5 meter-segments – 77 K)

Danfysik-SuperPower-Aarhus University (2012)

- Manufacturing:
  - 14 saddle coils bent after racetrack-like winding
  - Bending in the impregnation mould
  - Outward bending of the tapes (stress)
  - Pancakes joined by solders in coil ends (6-10 cm)
  - Empty space between ends and collar: paraffin







– Cu plates for cryocooler (x 2) mounting

(T_{op} cold mass~ 18 K)

Danfysik-SuperPower-Aarhus University (2012)

- Detection/Protection/Results:
  - Threshold: 90 mV (upper-lower by set of 2-3 coils)
  - 100 ms filter delay time
  - Dump resistor 1 Ω
  - Magnet inductance 1.49 H -> tau = 1.49 s

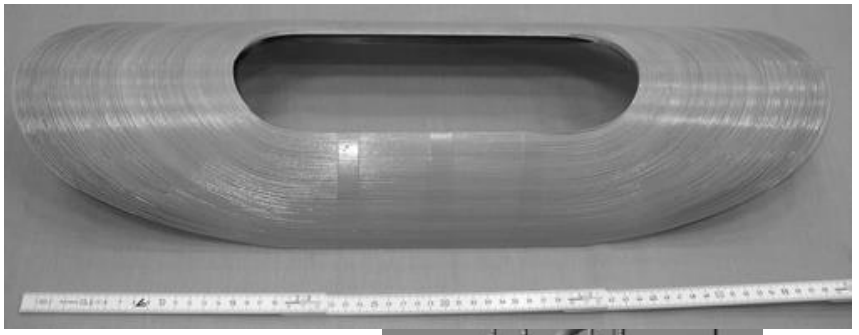
  - First ramp: quench at 70 A
  - 4 coils damaged (removed)
  - Re-assembly: quench at 130 A -> 2.09 T
  - Stable behaviour at 126 A -> 2.02 T
  - 2.6 T with iron poles inside aperture
  - Field quality -> dB/B ~ 10^{-3} at 26 mm radius (35 mm radius aperture)
    Coils removed taken into consideration

To have more: Nikolaj Zangenberg (nzg@teknologisk.dk)

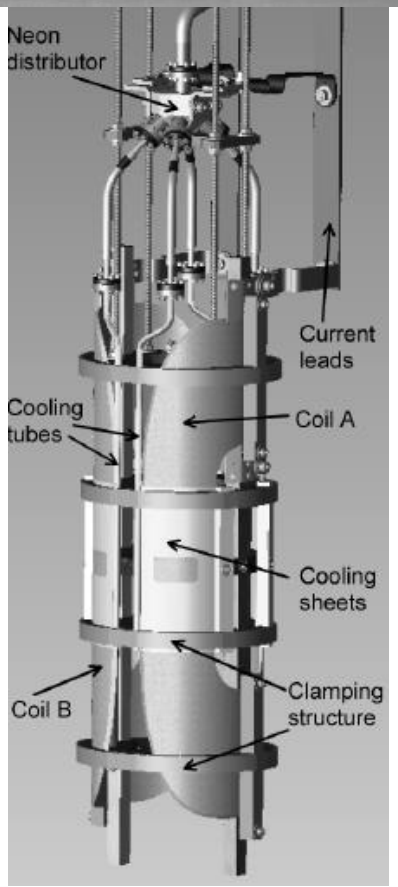
Siemens (2008)

- 2 saddle coil for rotating machine:
  - « Aperture » diameter: 199 mm
  - Straight section length: 200 mm (Total length 610 mm)
  - Nb of turns per coil: 310
  - Tape Ic @ 77 K and 1µV/cm (s.f.) = 98.3 A
  - Coil Ic = 50.8 A
  - Inductance of coil pair = 81 mH
  - Dipole field @ 30 K and 180 A = 0.342 T
- Tapes: Bi-2223/Ag (European High Temperature Conductors)
  - Length: 330 m per coil
  - Width: 4 mm ?
  - Thickness: 300 µm with insulation ?

Siemens (2008)



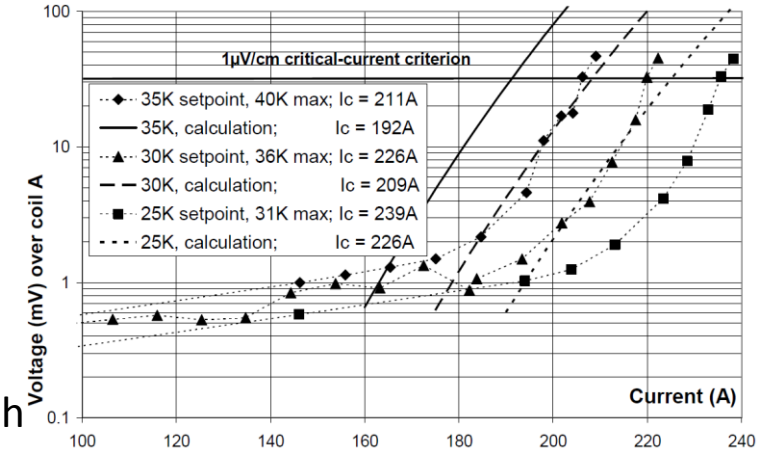
- Manufacturing:
  - Tape dry-wound in-plane (racetrack)
  - Bent onto a tube by pressing:
    - Torsion and easy bending of the HTS tapes
    - Tape tilted inwards at coil heads (as accelerator magnets)
    - To allow tape movement: spacers during winding removed for bending
      - Special software used to get the lengths, thicknesses and number of spacers
  - Winding impregnation with Epoxy
  - Coil assembled in a dipole configuration

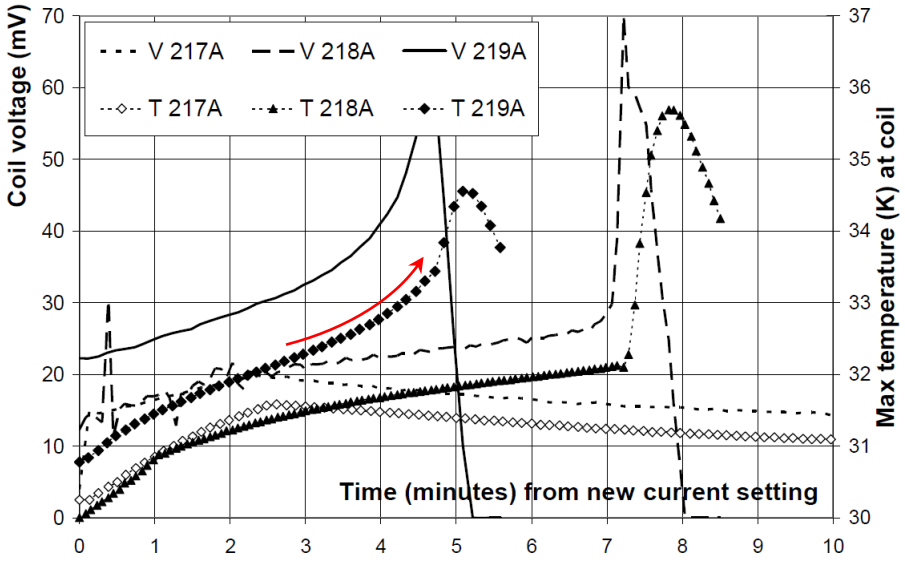


- Cooling: liquid neon (~ 30 K)
  - Copper cooling sheets (filled Epoxy attached to straight part)
  - Soldered with cooling tubes
  - Heads cooled by heat conduction
  - Supporting structure
    - Coil on glass reinforced polyester strutcure
    - Clamped with stainless-steel

Siemens (2008)

- Tests at 25, 30 and 35 K:
  - First cool-down -> coil B no more superconducting
    - Too fast cooled-down cooling tube contraction not followed by winding
    - Outer turns damaged by the cracking
  - Several slow cool-downs of coil A: no damage
  - n-value = 20-25 (no degradation)
  - 180 A continuously applied at any temperature with voltage < 1µV/cm



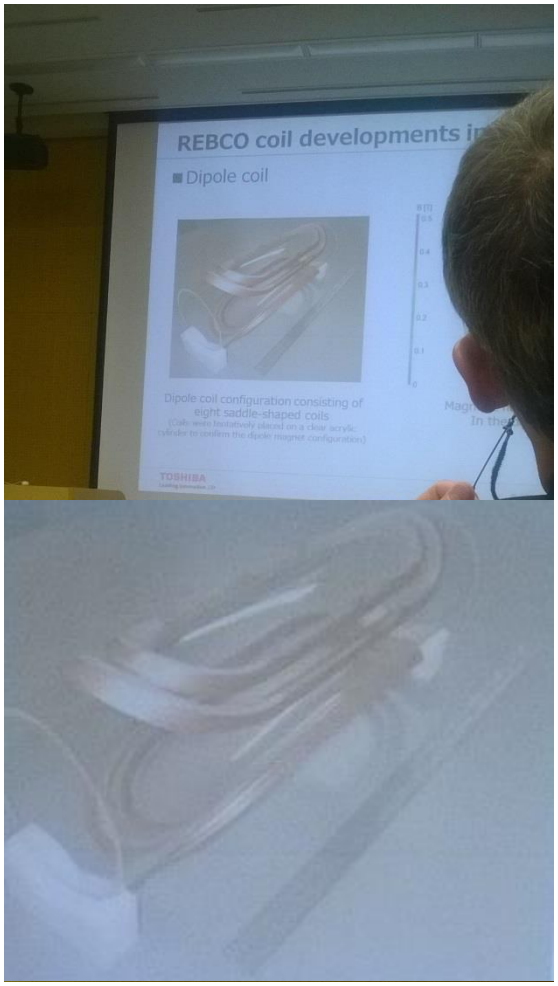


coil head temp. sensor

- Protection
  - Current switched off at 80 mV
  - At 219 A quench annonced by temp.

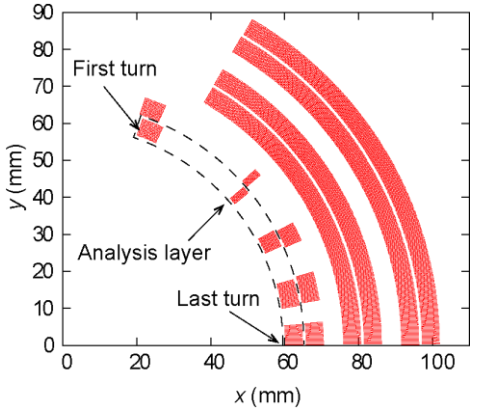
Toshiba – Kyoto university (2014)

- HTS dipole based on 8 saddle coils



To get more: kenji2.tasaki@toshiba.co.jp

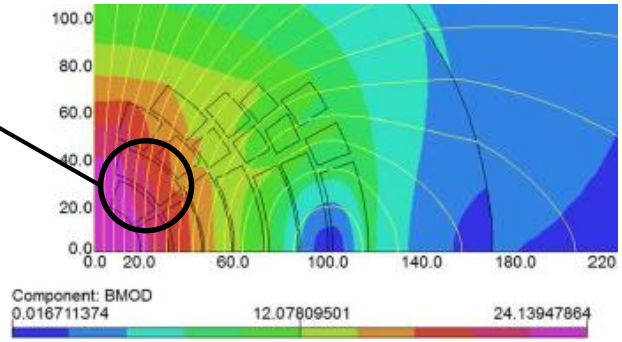
- cosine-theta dipole magnet for rotating gantry for carbon cancer therapy ?



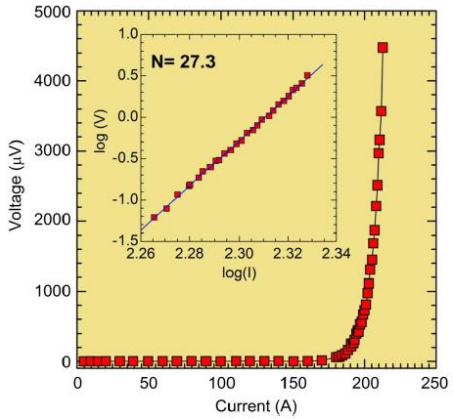
To get more: amemiya.naoyuki.6a@kyoto-u.ac.jp

Brookhaven National Lab (2014)

- REBCO pole coils for hybrid cos-theta magnet
- 2 pole coils fabricated and tested @ 77 K



- 300 mm long
- 50 mm radius mandrel
- pole coil means ~70° azimuthal location
- 20 turns
- 12 mm tapes from SuperPower
- 25 µm Kapton CI wrapped 30 % overlap
- tape activated 30 min @ 225°C (easy handling)

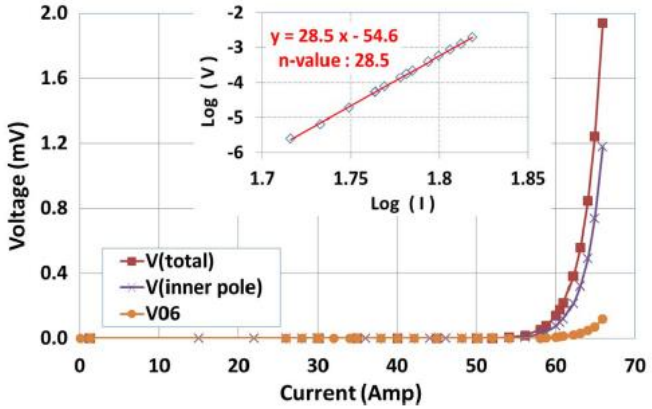


- Ic coil = 204 A (1 µV/cm)
- Bpeak = 0.23 T
- 14 voltages tapes
- n-value = 27 -> no degradation during instrumentation

Brookhaven National Lab (2014)

- 300 mm long
- 50 mm radius mandrel
- pole coil means ~70° azimuthal location
- 45 turns
- 4 mm tapes from SuperPower
- co-wound with 38 µm kapton tape

- Ic coil = 67 A (1 µV/cm)
- Bpeak = 0.24 T
- 14 voltages tapes
- n-value = 28.5



Future program:

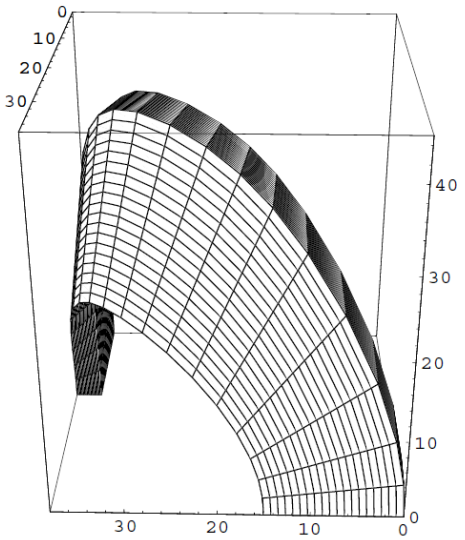
Next step Phase I : Full hybrid cross-section / 77 K and 4 K tests

Phase II : Coil made of clad tape (2 single layer tapes soldered together as EuCARD)

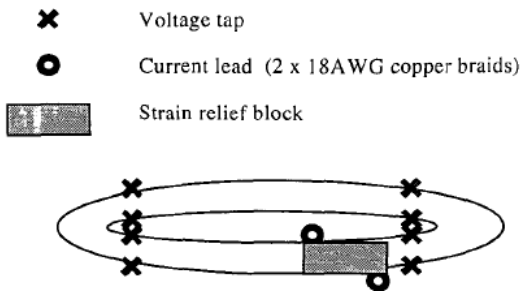
To have more: Ramesh Gupta (gupta@bnl.gov)

AmSC – BNL – Cornell University – FNAL (1999)

- BSCCO 2223 saddle coil for quadrupole magnet
- Rectangular straight section



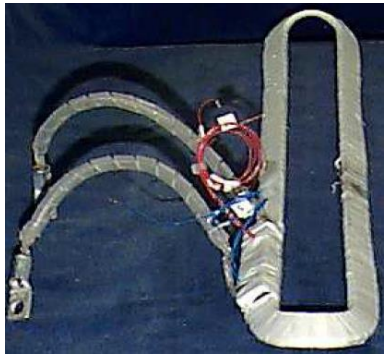
  - 380 mm long (334 mm straight section)
  - 35 mm radius mandrel
  - 32 turns (2 x 30-m tapes in parallel)
  - 2.7 mm x 180 µm tapes from AmSC
  - Min. bending radius 12 mm
  - Fiber-glass wrapping of winding + vacuum impregnation
  - 8 voltages tapes (inner and outer most turn at straight section extremities)

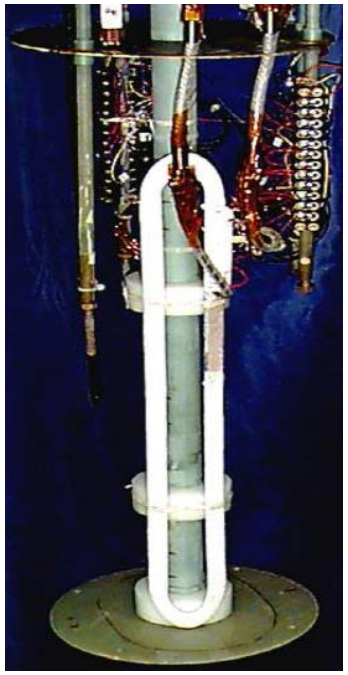


AmSC – BNL – Cornell University – FNAL (1999)

- Ic coil = 43 A @ 77 K and 1µV/m
- Ic coil = 240 A @ 4.3 K and 1µV/m
- n-value ~ 7
- 15% degradation due to bend strain

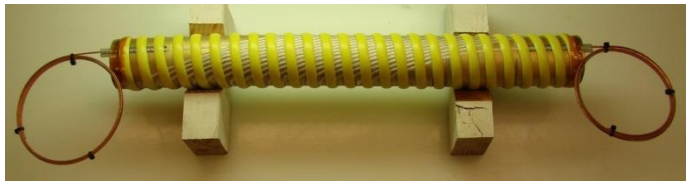
- Estimation Ic coil = 172 A @ 30 K and 1µV/m leading to 5500 A-turn.
- Losses: 0.4 W @ 172 A, 30 K per coil.





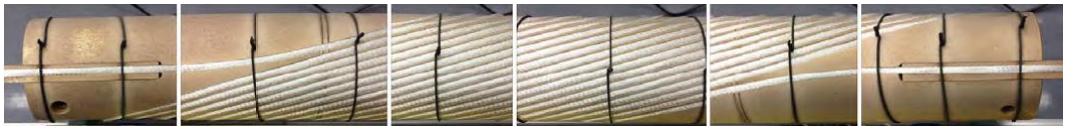
LBNL (2014)

- Proof-of-concept Bi-2212 canted-cosine-theta coil, named BIN2

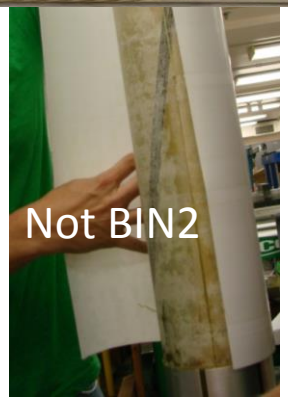


  - 500 mm long (100 bar furnace size of ASC-FSU)
  - 38.8 mm aperture radius
  - 68.6 mm radius outer shell made of Al
  - 2.4 mm diameter 6-around-1 cable (20 turns)
  - 0.8 mm Bi-2212 wire
  - Alumin-silica braided insulation
  - Al-Bronze alloy 642 mandrel (groove 2.7 x 3 mm²) – machine in 2 hours
  - Bore rough-machined/heat treated 888°C 5 hours/fine-machined + groove milling

  - 1 bar heat treatment (LBNL furnace)

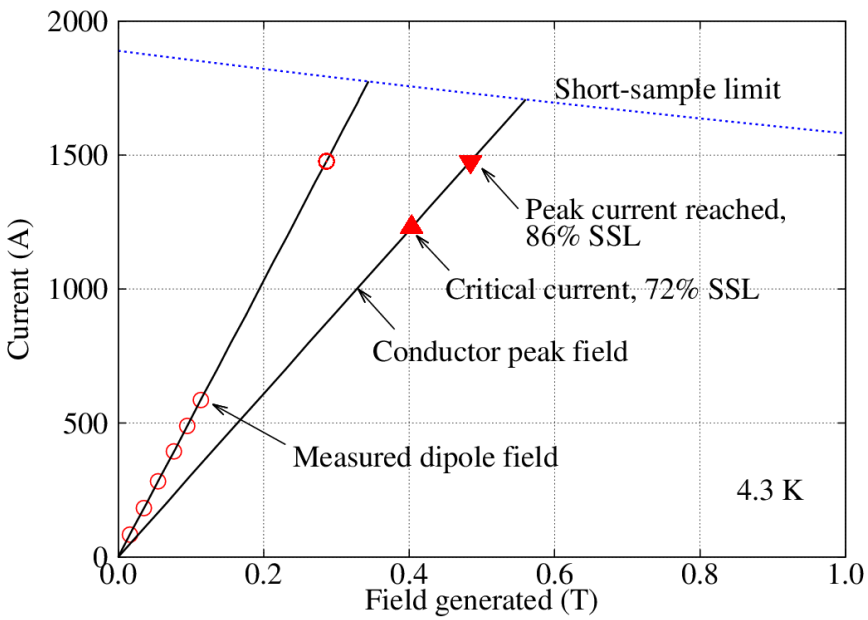


  - Potted with bees wax to give more flexibility (wrapped with teflon sheet + sealed with heat shrink tube and clamped metal sheet)



LBNL (2014)

- Test results of half of a CCT, inner coil of BIN2
  - I_c coil = 1230 A (0.1 μV/cm, n = 15)
  - > 72 % short sample limit
  - J_e = 350 A/mm²
  - Cycled to 1400 A for a few times without degradation
  - Excellent agreement between measured dipole fields and calculation

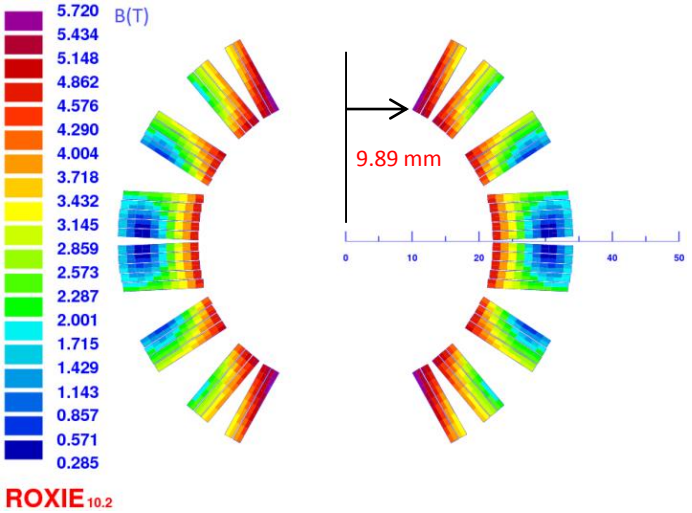


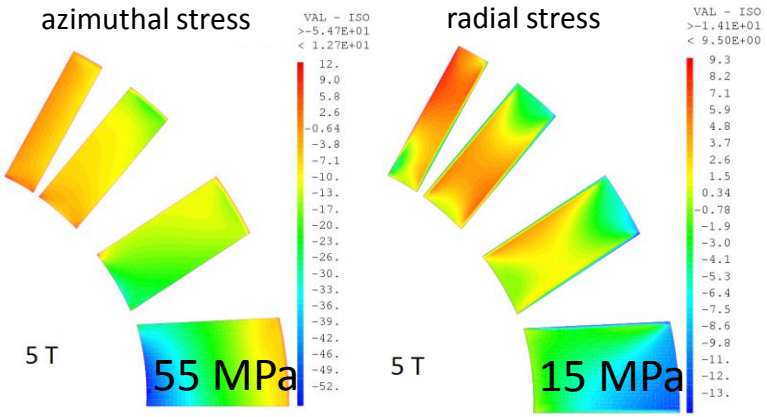
- Red: measurements
- Black lines: calculated load lines
- Short-sample: 1708 A

To have more: Shlomo Caspi (s_caspi@lbl.gov)

CEA (In Progress)

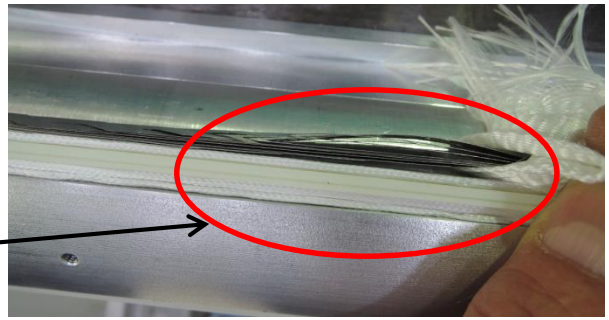
- Cos-theta dipole insert made of REBCO-Rutherford cable (EuCARD2*)
  - 700 mm long (~200 mm straight section)
  - 22 mm radius mandrel
  - 14 turns
  - REBCO Roebel cable (KIT)
    - 15 tapes (BRUKER): 5.5 mm wide, 0.15 mm thick
    - 12-mm wide cable, 226 mm TP, 30°
  - Minimal bending radius ~8 mm
  - ~100 µm thick fiber glass
  - Impregnation (mandatory)
  - 5 T central field stand-alone (I = 11 680 A)





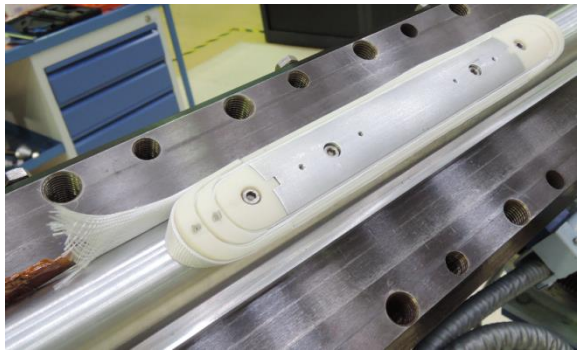
*baseline: J. van Nugteren and G. Kirby (CERN) (see ref).

CEA (In Progress)

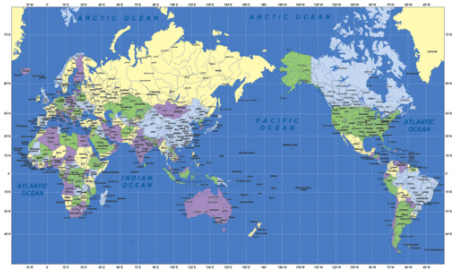


- Winding tests with dummy cable (1st turns)
  - Differential length in coil ends leads to:
    - buckling effects of the cable
    - tension not evenly distributed over tapes (Jaakko S. Murtomaki CERN -> 5 kg max)
  - 3D printed end spacers
  - One dedicated spacer per turn (2-m hardway)

- Full length test planned in May
  - 13 m dummy Cable from KIT
  - Fiber glass insulation



Wishes overview around the world



- Michigan State University, Al Zeller: «We most likely in the future have HTS sextupole and octupole inserts in the quadrupoles that are approximately cos(n-theta)»
- KEK, Tatsu Nakamoto: « HTS cos-theta magnet R&D in the near future »
- FNAL, Alexander Zlobin: « Depending on budget the real work on HTS dipole insert may start only next year »
- IBS, Jongwon Kim: « We are doing theoretical study on cos-2theta HTS quadrupole, but no current plan to build one »
- LBNL, Arnaud Godeke: « Winding of a 4 T BSCCO Rutherford CCT insert »
- EuCARD3?

Thank you

Acknowledgments to:

Zlobin Alexander (US), Zeller Al (US), Zangenberg Nikolaj (UE), Xu Qing-Jin (China), Vysotsky Vitaly (Russia), Parizh Michael (US), Ogitsu Toru (Japan), Nakamoto Tatsu (Japan), Molodyk Alexander (Russia), Larbalestier David (US), Kozub Sergey (Russia), Kim Jongwon (South Korea), Gupta Ramesh (US) , Durante Maria (UE), Cooley Lance (US), Cha Gueesoo (South Korea), Caspi Shlomo (US), Amemiya Naoyuki (Japan)

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