High current probe for $I_c(B,T)$ measurements with ±0.01 K precision

HTS current leads and active temperature stabilization system

Christian Barth, Marco Bonura and Carmine Senatore
Department of Quantum Matter Physics & Department of Applied Physics, University of Geneva, Geneva, Switzerland

UNIVERSITÉ DE GENÈVE
FACULTY OF SCIENCE
Department of Quantum Matter Physics

Abstract

The current carrying capabilities of Rare-earth-$Ba_2Cu_3O_{7-x}$ (REBCO) coated conductors (CCs) as well as $Bi_2Sr_2Ca_2Cu_3O_{10+x}$ (Bi2223) tapes have considerably improved in the recent years, and this has practical consequences on the requirements of the measurement equipment. We have designed, constructed and tested a probe for high current, high precision critical current measurements in liquid helium and in gas flow at different temperatures. To minimize the ohmic heating and the thermal conduction losses, the probe employs HTS current leads rated at 2000 A, which are cooled by the exhaust helium gas at temperatures below 70 K. An active temperature stabilization system keeps the sample temperature constant at the target during current runs. It consists of a proportional - integral - differential (PID) loop that controls heaters located inside the connection between the current leads and the sample. Any heat generated at the contacts or during the superconducting transitions at the sample is subtracted from the output of the PID algorithm. This compensates for the current induced heating effects, resulting in a temperature stability of ±0.01 K during critical current measurements, even in gas flow.

We present the design of the probe and data collected on HTS from different manufacturers, which highlight the performance of the system.

Motivation

Future accelerator magnets: 16 - 20 T
Next gen. >1 GHz NMR magnets: > 23.5 T
} beyond field limits of LTS

Supercond. rotating machines: 20 – 40 K
Supercond. transformers & cables: ≥ 65 K
} beyond temperature limits of LTS

→ HTS, especially REBCO tapes are receiving increasing attention

HTS impose new measurement requirements:
- anisotropy + high currents → enormous critical current if field || ab
- operation possible >> 4.2 K → temperature dependence important

Existing measurement equipment at UniGe (LTS $I_c(B)$ probe) insufficient:
- ≤ 1000 A at 4.2 K
- ≤ 250 A in gas flow with ±0.5 K precision

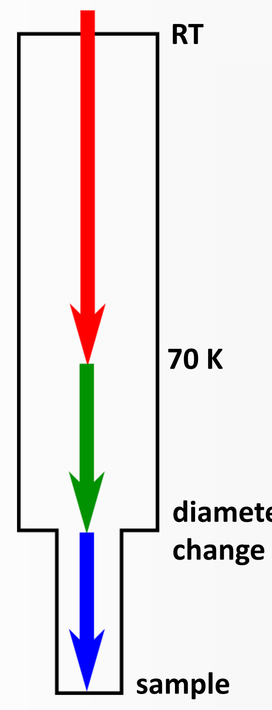
→ new high current $I_c(B,T)$ probe

Goals and solutions

Goals:
- 2 kA at 4.2 K and 1 kA in gas flow
- maximizing temperature stability
- minimizing He boil-off & measurement noise
- demountable, vacuum operation possible

Solutions:
- current leads demountable in 3 segments
  - RT → 70 K: concentric brass tubes, He return gas cooled
  - 70K → diameter change: copper stabilized REBCO
    - 10 stacks of 4 tapes (4 mm wide) per lead
    - SuNAM: high temp., low field performance
    - He return gas forced around tapes, G10 structure
  - diameter change → sample: stabilizer free REBCO
    - 4 tapes (12 mm wide) per lead
    - G10 structure, no metal except REBCO tapes
    - SuperPower: low temp., high field performance

  → high currents & minimal thermal input



  - all connections through clamping
    - Au coated REBCO tapes on Au coated oxygen free Cu
    - 316L pressure plates with indium for force distribution

  → fully demountable, all REBCO tapes can be replaced without soldering
- active temperature stabilization
  - I_c measurement in const. temp. gas flow increases sample temp.

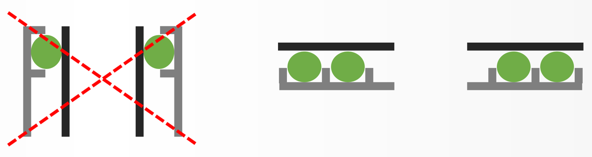
    → compensate with gas flow temp: ✗ response too slow

    → compensate at the sample: → 2 PID loops
    - 1st : gas flow slightly below target temp.
    - 2nd: heater in the sample contacts to reach target temp.

      → power deposited at sample during I_c measurement is determined and subtracted from 2nd PID output

  → strongly improved temp. stability in gas flow as currents do not heat the sample
- vacuum tight probe head
  - flat connections & double O-ring seals

  → outer sealing ring protected from the cold

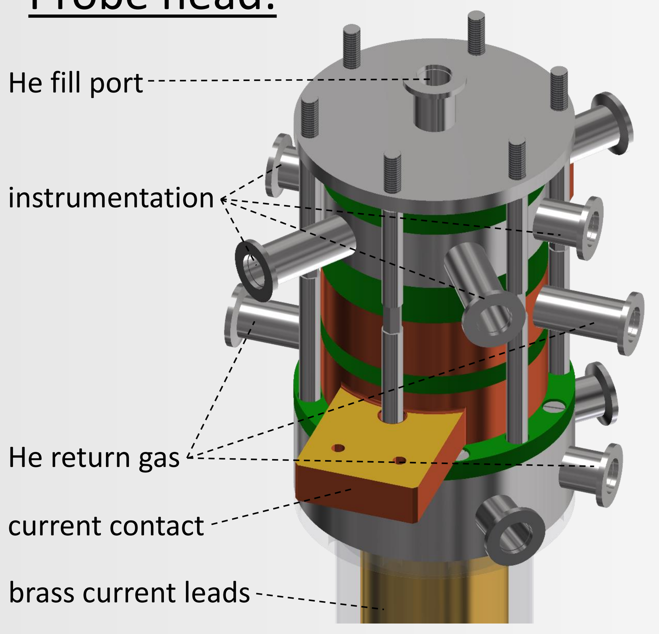


- minimize measurement noise
  - separate paths for instrumentation wires and He return gas
    - cables and connectors at constant temperature

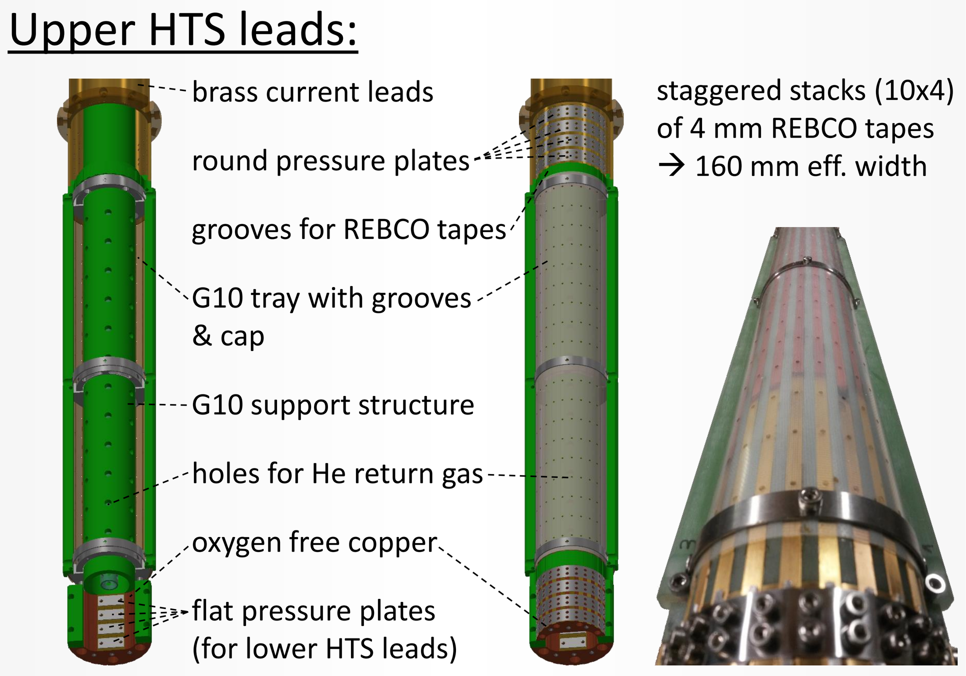
  → prevents fluctuations of thermal voltages during current runs

Design (upper part)

Probe head:

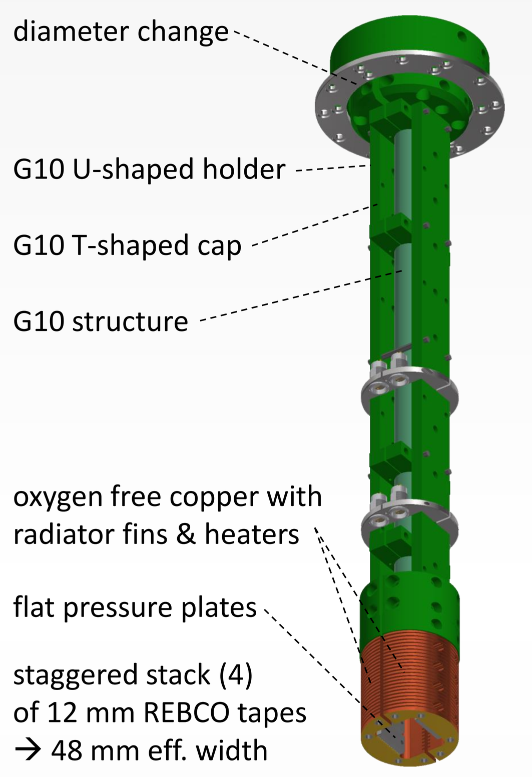


Upper HTS leads:

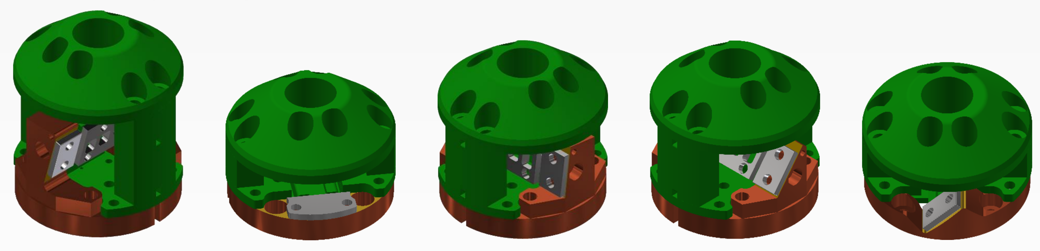


Design (lower part)

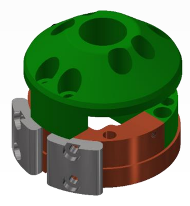
Lower HTS leads:



Sample adapters:
- ϑ = 15°, -7.5°, 7.5°, 15°, 22.5°, 30°, 37.5°, 45°, 90°: 800 A



- ϑ = 0°: 2 kA at 4.2 K & 1.5 kA in gas



- LTS barrel: 1.5 kA at 4.2 K

- Cernox temp. sensor on sample
- demountable → sample can be prepared apart from the probe

Protection:
- voltage taps at HTS leads (upper + -, lower + -), separate hardware QD
- Cernox temp. sensors above, below and between the lead segments

Performance

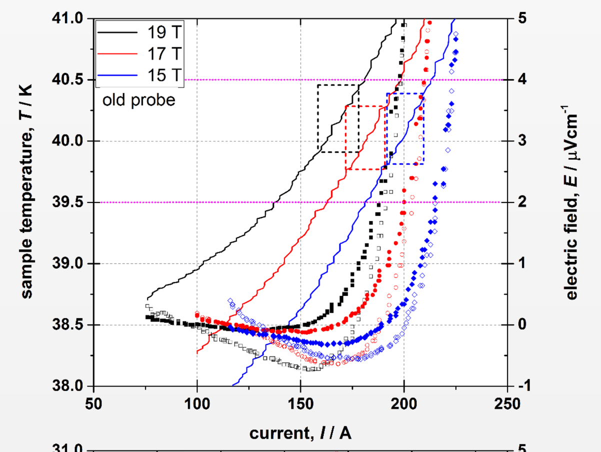
HTS current leads
- successfully tested till 2 kA at 4.2 K
- 80 nΩ*mm² contact resistance

  → 12 W / lead at 2 kA

→ at 4.2K, leads cooled down during current run. Negligibly lead temp. increase in gas flow runs

Example 1: Bruker HTS #16016
- 4.1 mm wide, field || ab
- old probe *(40 mm long sample)*
  - temp. increases strongly during run
  - start temp has to be chosen adequately

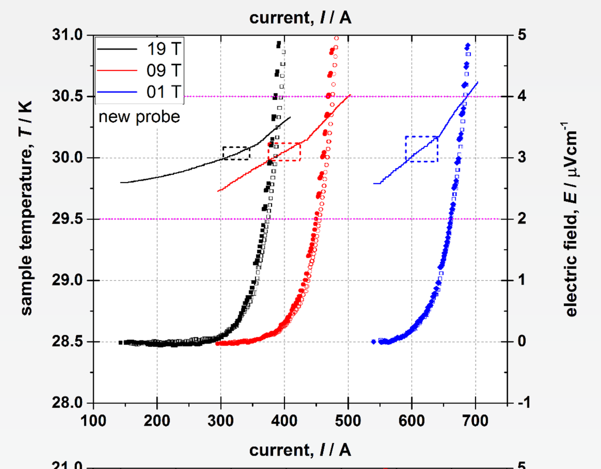
    → up to 250 A with ±0.5 K precision



- new probe *(125 mm long sample)*
  - lower measurement noise
  - temp. increases slightly during run
  - start temp has to be just below target

    → up to 1 kA with ±0.5 K precision

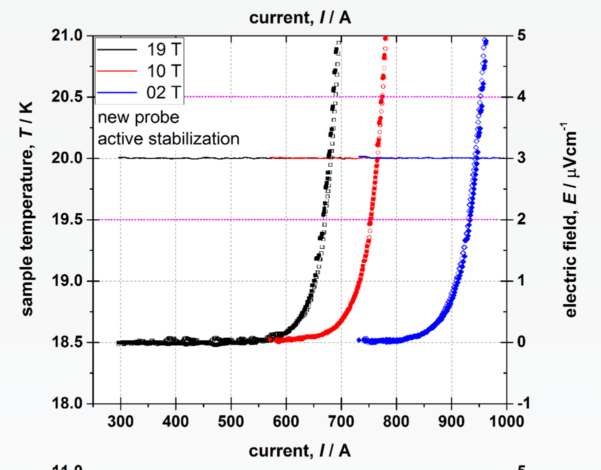
    → 4x improvement in current



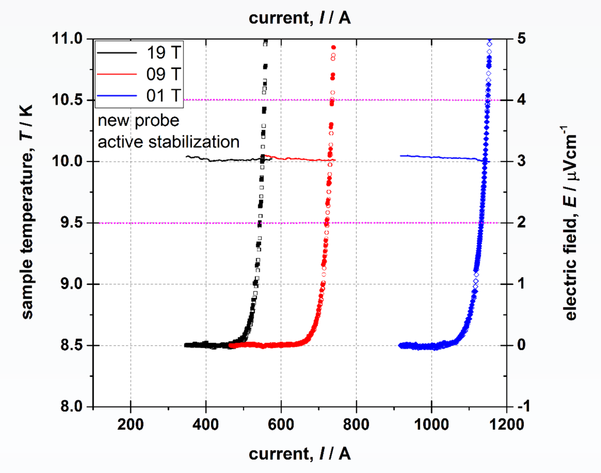
- new probe with active temp. stabilization
  - temp. constant during run
  - gas flow 1.0 K below target
  - 1.2 W avg. heating at the sample

    → up to 1 kA with ±0.01 K precision

    → 50x improvement in temperature



Example 2: Sumitomo HT-NX Bi2223
- 4.2 mm wide, field || ab, new probe
  - gas flow 2.5 K below target
  - 4 W avg. heating at the sample



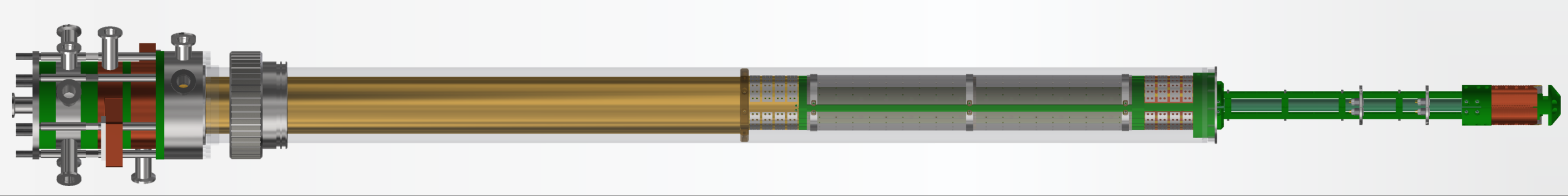
He efficiency
- old probe
  - 6 l of lHe for cooldown
  - significant standby & measurement boil-off (≈3 l of lHe to reach 1 kA)
- new probe
  - 3 l of lHe for cooldown
  - low standby & measurement boil-off (<1 l of lHe to reach 1.5 kA)

  → > 3x improvement in He efficiency

Summary

- 2 kA at 4.2 K and 1 kA in gas flow goal exceeded ✓
- temperature stability vastly improved ✓
- superior He efficiency and measurement noise ✓

6 months of successful operation with no current lead quench



We acknowledge and thank Damien Zurmuehle as well as Roland Pellet and his team from the mechanical workshop (UniGe) for their amazing work in machining this measurement probe. Without them, none of this would have been possible. Furthermore, we acknowledge Christian Lange and Frank Gröner (KIT) for their help with the gold coating. We also thank Drew Hazelton (SuperPower Inc.) for providing the REBCO tapes free of charge. Financial support was provided by the Swiss National Science Foundation (Grant No. PP00P2_144673 and Grant No. 51NF40-144613).