Method of Manufacturing Fast Ramping Non-Insulated HTS Pancake Coils

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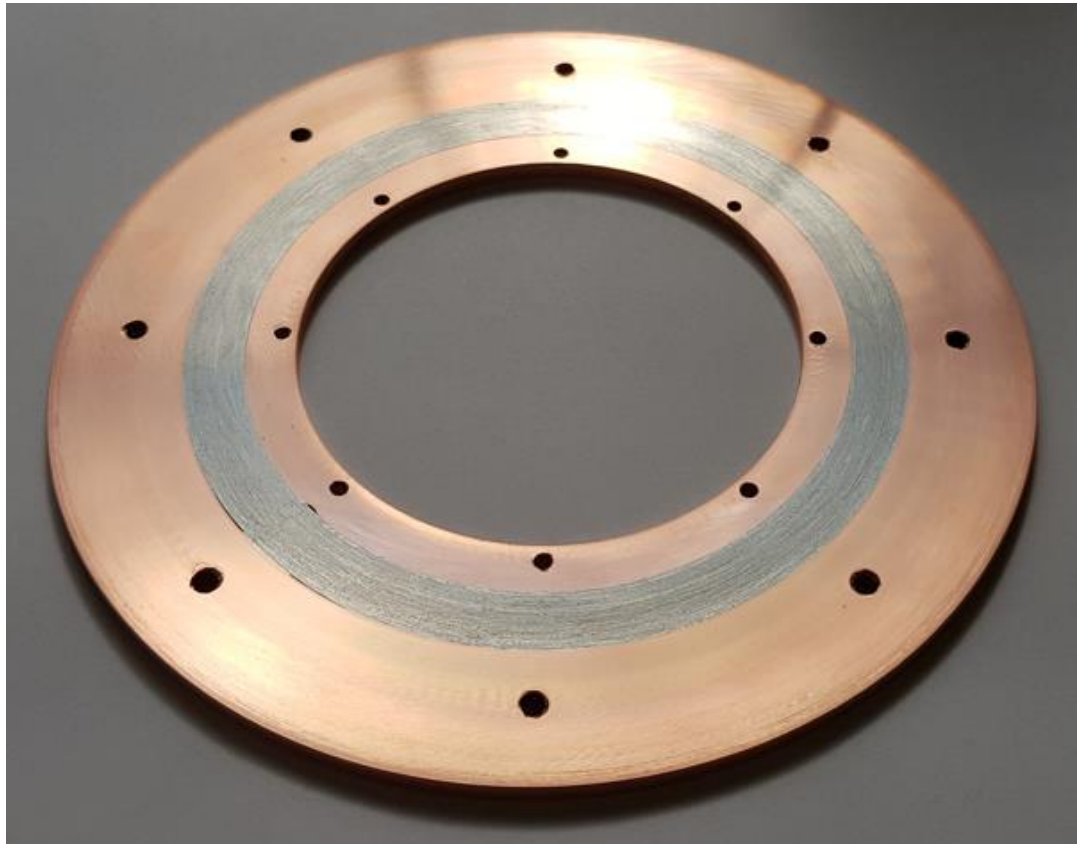
Quest to control the turn-to-turn resistance of a NI coil

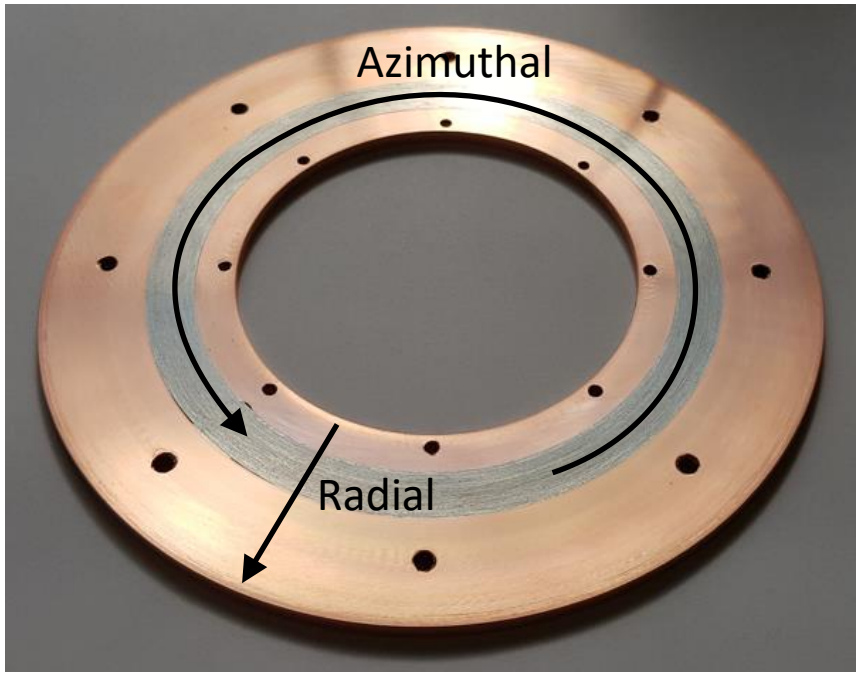
- Quench protection of HTS coils is not trivial.
- Undetected hot-spot doesn't propagate quickly.
- Non-Insulated coil technology offers a solution, but creates a new challenge: time constant.
- Time constant high enough to charge/discharge the magnet.
- Time constant low enough to survive a quench.
- Controlling the turn-to-turn resistance:
  - Winding without insulation,
  - Fully soldering the coil pack,
  - Co-wound (stainless-steel) metal strips,
  - Other solutions?

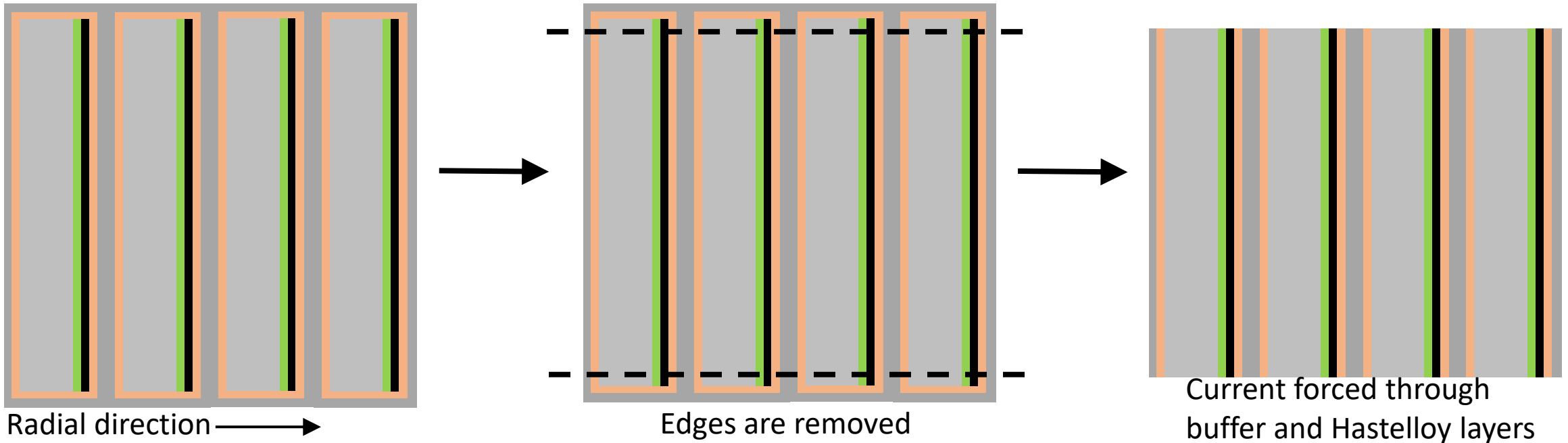


How can we reduce the time constant of a fully soldered coil?

The Concept

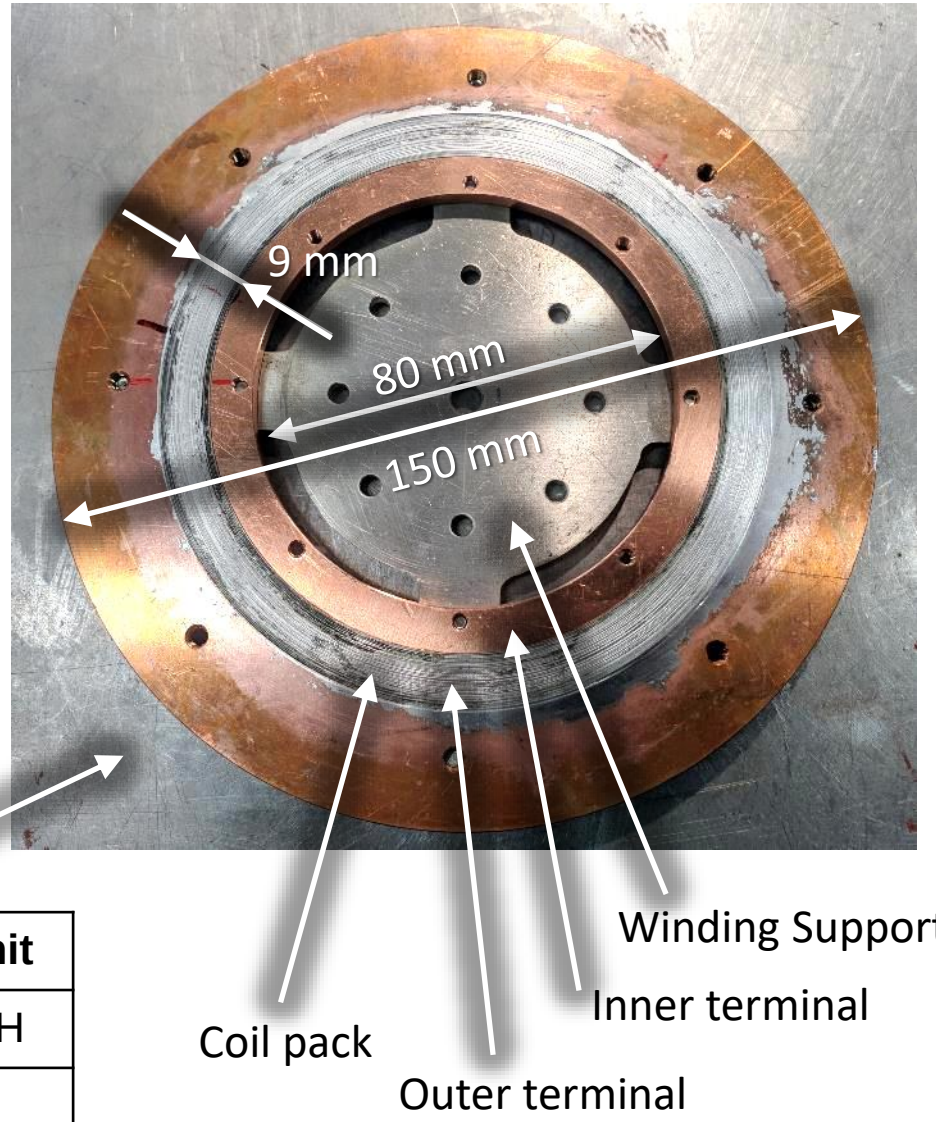
- Surround copper & solder stabilizer on tape carries majority of the current in normal state.
- Buffer layers are insulating in bulk. Imperfect in thin layers, form high-resistance barrier.
- In case of a hot spot, current bypasses primarily through the surround copper stabilizer and solder on the tape edge.
- Removing the edge of a HTS pancake coil -> current is forced through the high-resistance buffer layers and Hastelloy.





Preparation of the Pancakes

- Three demonstrator pancakes were prepared.
- Coil winding wound on the outer copper terminal.
- Coil packs of all three pancakes are fully soldered to maintain thermal and mechanical stability.
- First pancake was soldered in a SnPb bath. The other two were heated and solder was added manually to the coil pack until saturation.
- Inner copper terminal was shrink-fitted, all other connection are soldered.



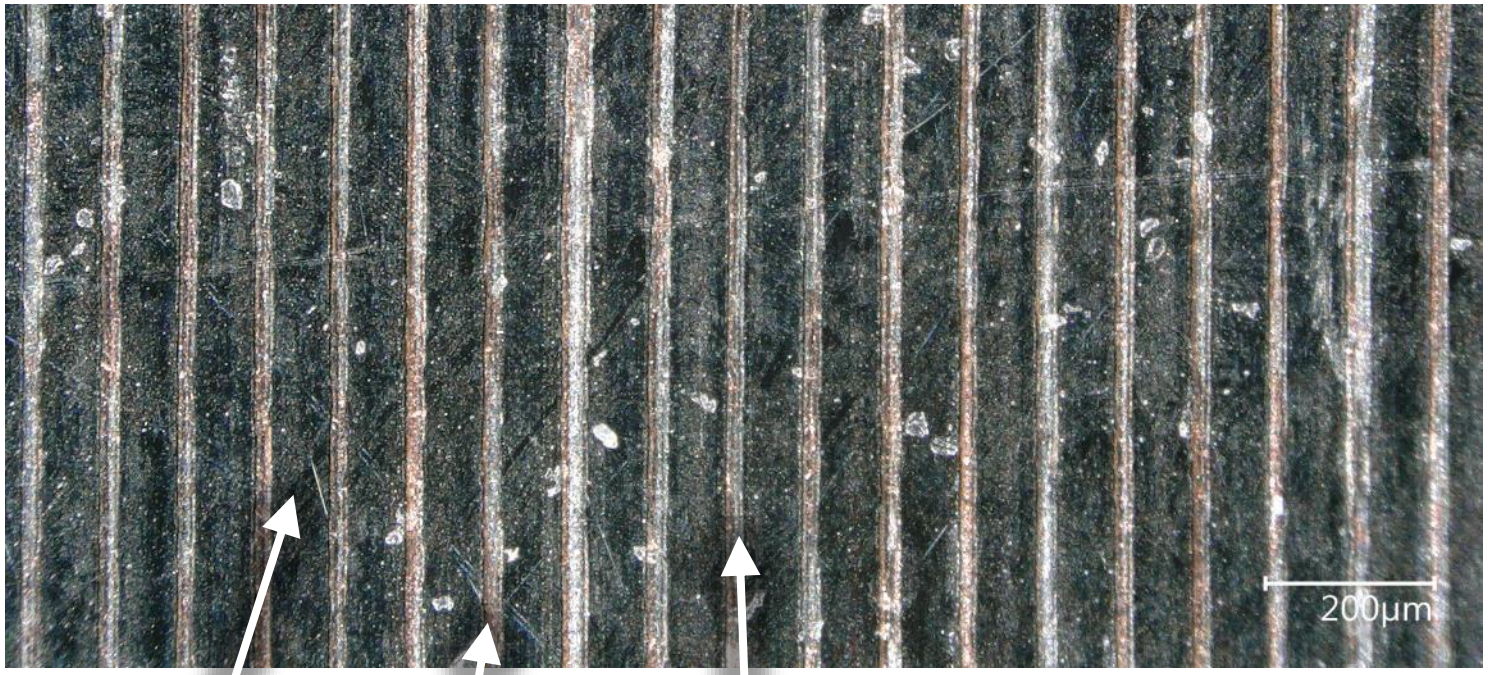
Pancake 2 after soldering

	Pancake 1	Pancake 2	Pancake 3	Unit
Inductance	1.9	2.0	2.0	mH
Turns	91	96	96	-
Thickness before machining	4.0	4.0	4.0	mm
Thickness after machining	3.3	3.7	3.7	mm

Removing the copper and solder edge

- The copper and solder edge was removed mechanically.
- 0.35 mm was removed on either side for pancake 1, and 0.15 mm for pancakes 2 & 3.
- Low amount of defects visible from top of the coil pack (unpolished).

Picture by M. Crouvizier, CERN



Hastelloy, 60 µm

Surround copper plating, 5 µm

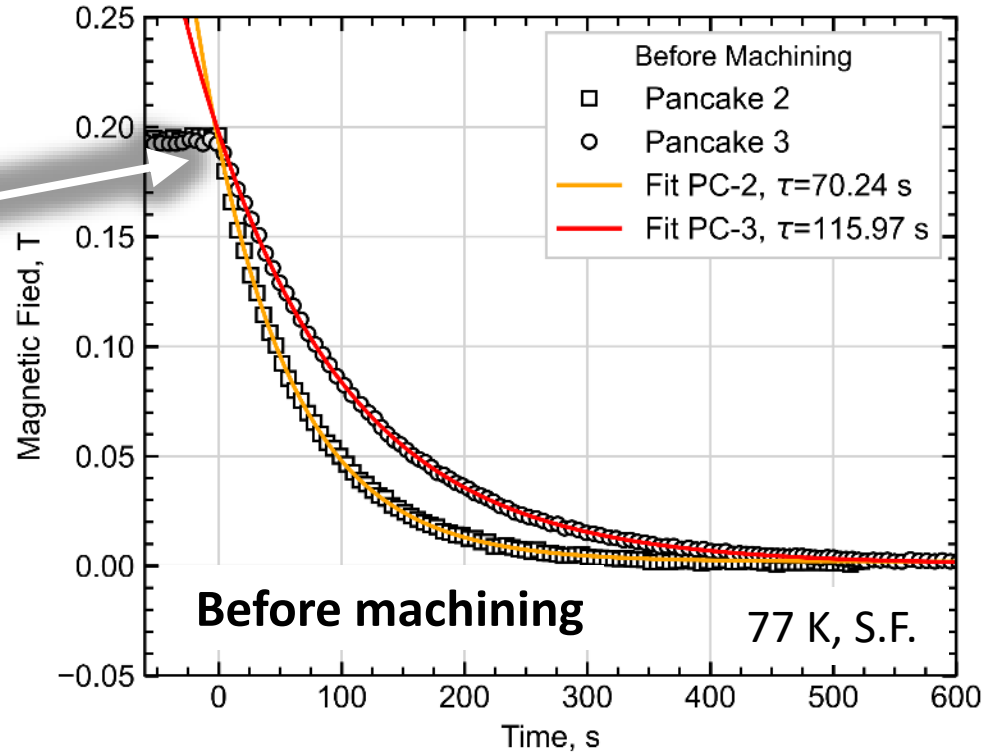
SnPb solder in between tapes, ~10 µm

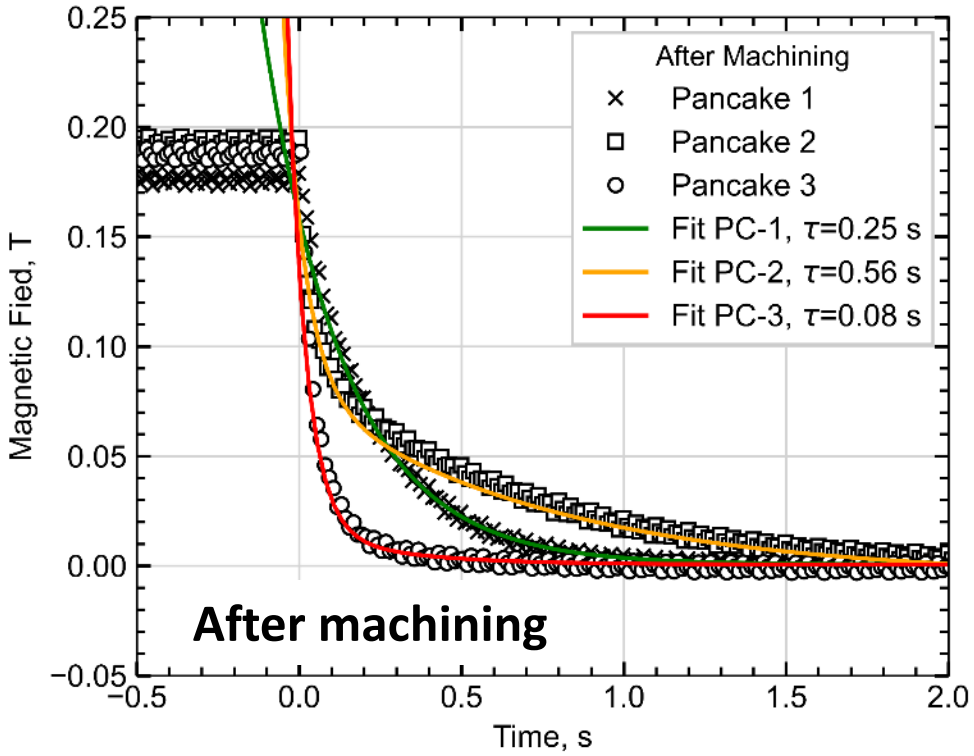
Top view, unpolished, after machining.

Time constant after machining vs. Current

- Pancake 1 was used to test the manufacturing steps and not tested before machining.
- Pancakes 2 & 3 were tested before and after machining.
- The time constant of pancakes 2 & 3 are 70 and 116 s before machining at 77 K.
- The time constant of pancakes 1, 2 & 3 are 0.25, 0.56 and 0.08 s after machining.
- **<u>Reduction in time constant by a factor of 500-1000.</u>**

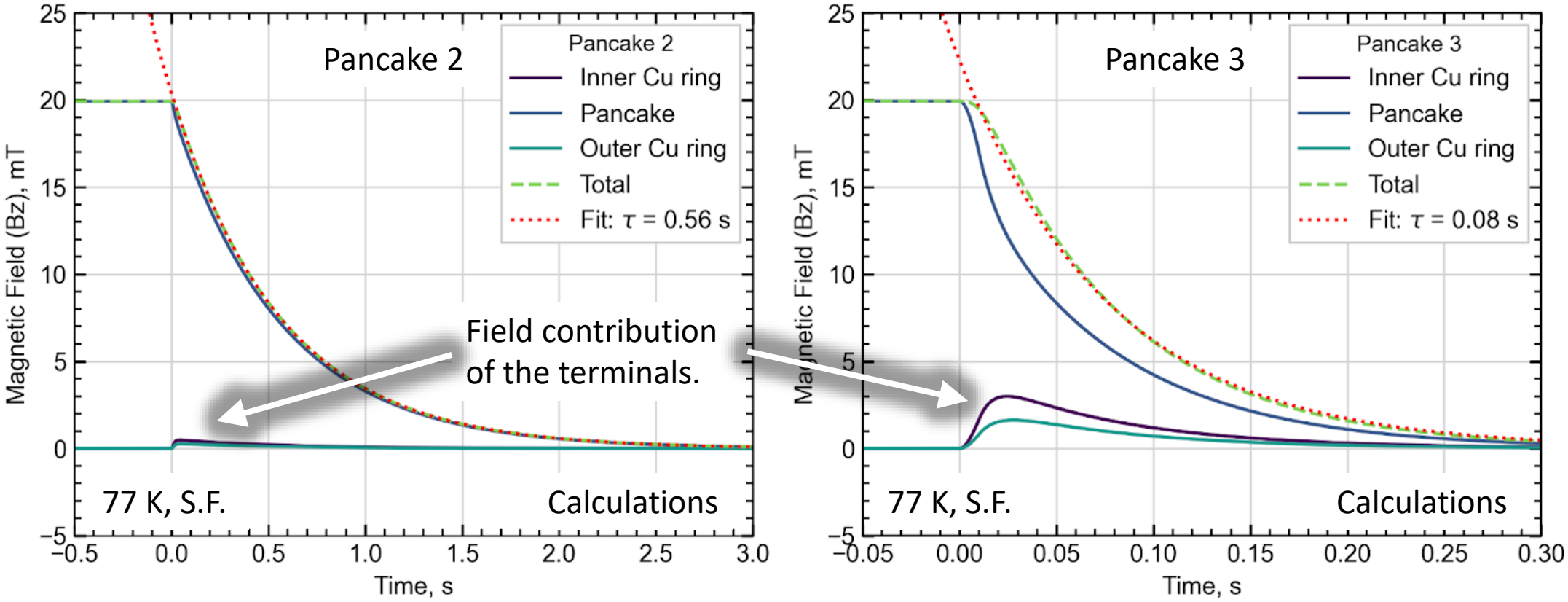
Opening of an electrical breaker





Induced Currents in the Terminals

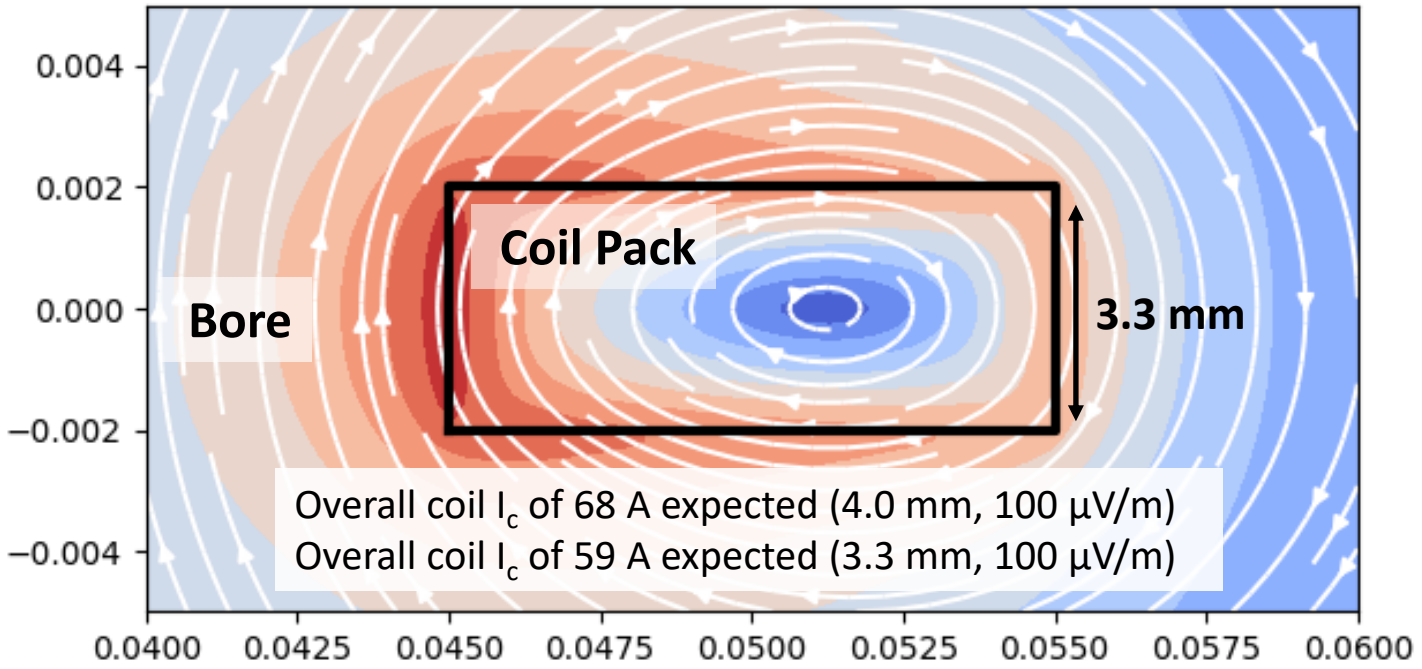
- Time constant is determined by the rise/decay of magnetic field.
- Fast ramp up/down -> induced current in the joint terminals -> effects magnetic field.
- Calculations show the influence of the terminals is minimal for pancake 2.
- For pancake 3 (measured τ of 80 ms), the terminals contribute about 20 ms to the time constant.



Pancake 1: Electrical Performance at 77 K

- Pancake 1 was not tested before machining, meant to be just a production prototype.
- Soldered in bath of SnPb, observed alloying between solder alloy and silver/copper tape coating.
- Inner few turns were removed after soldering, as bare SC was visible.
- Thickness of 3.3 mm after machining -> expected I_c of 59 A (3.3 mm, 77 K, S. F., 100 µV/m).
- I_c of 40 A and a quench current of 65 A (after machining) -> 32 % lower than expected.

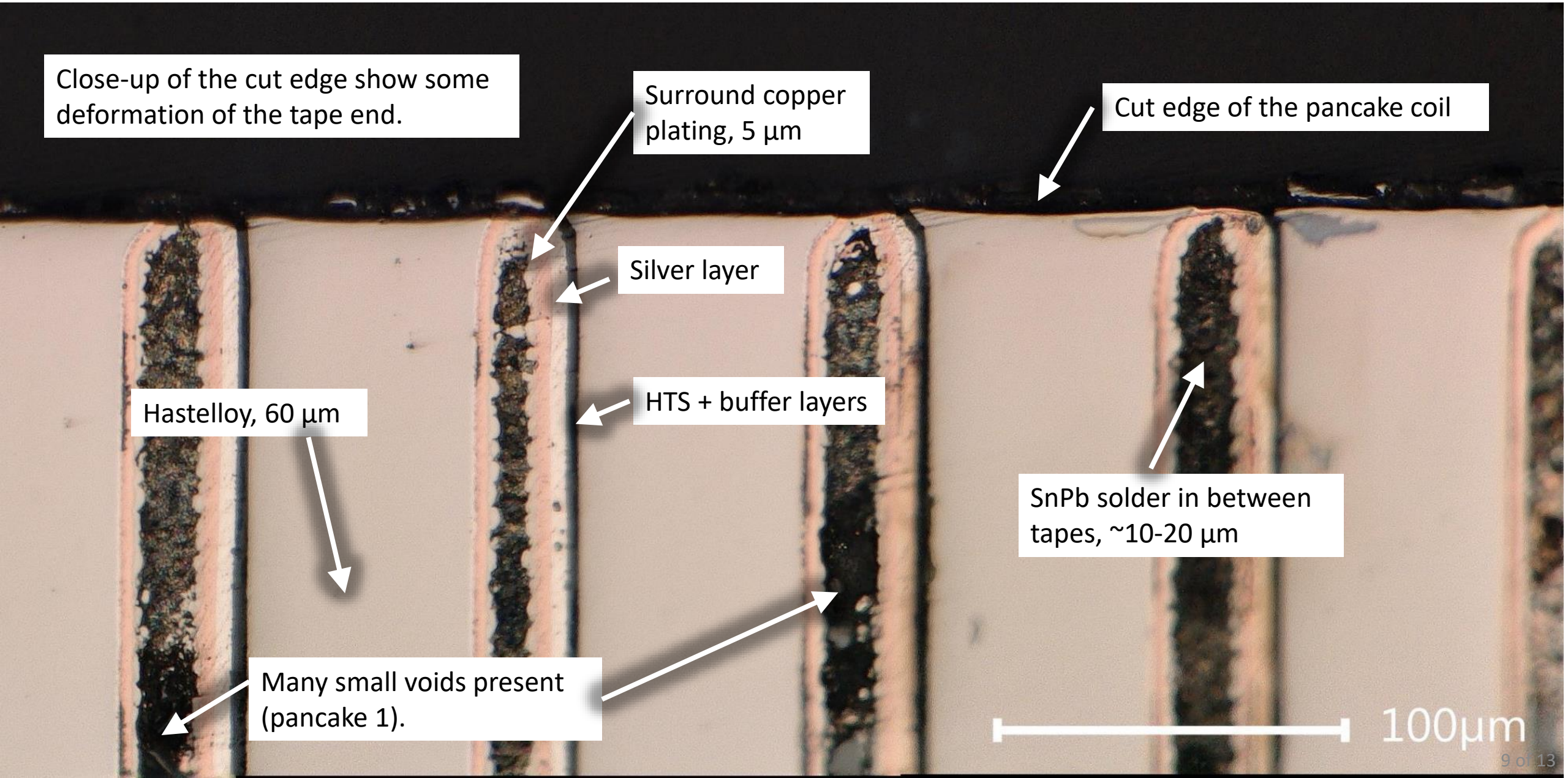
Pancake 1 in a SnPb bath.



Cross-Sectional View Pancake 1

Picture by K. Buchanan, CERN

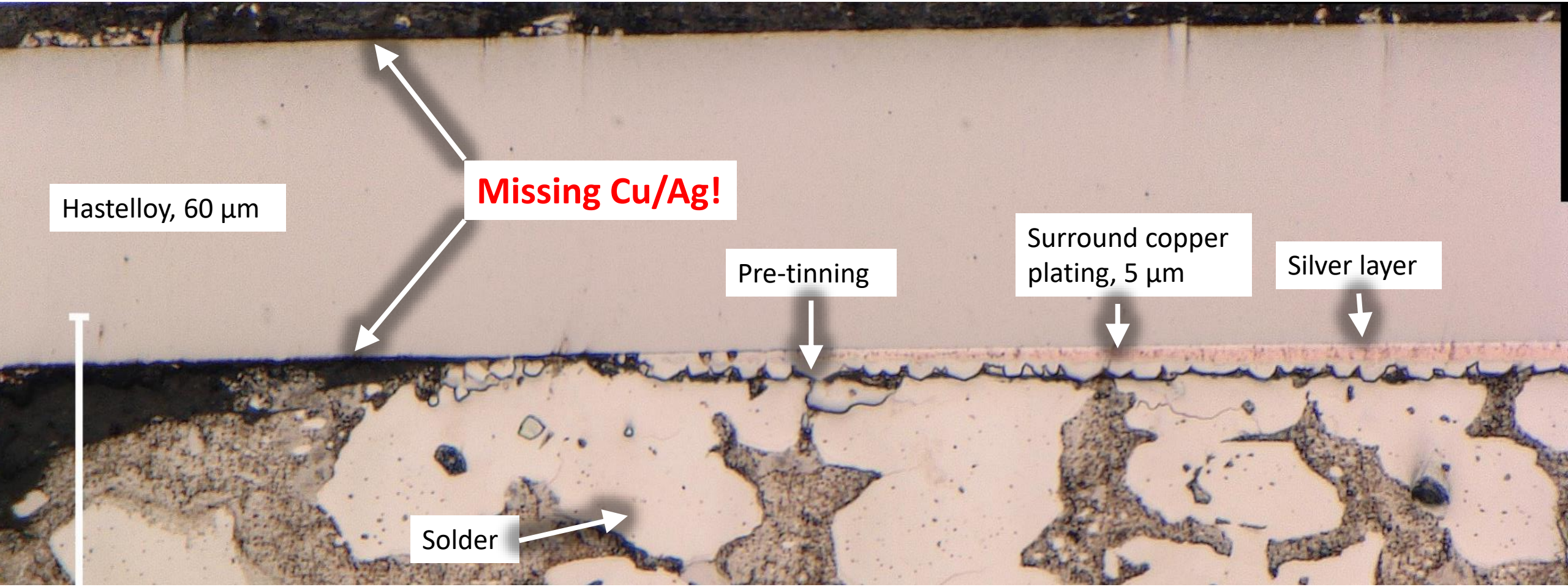
Pancake 1
cross-sectional view



Missing Surround Cu plating / HTS!

Picture by K. Buchanan, CERN

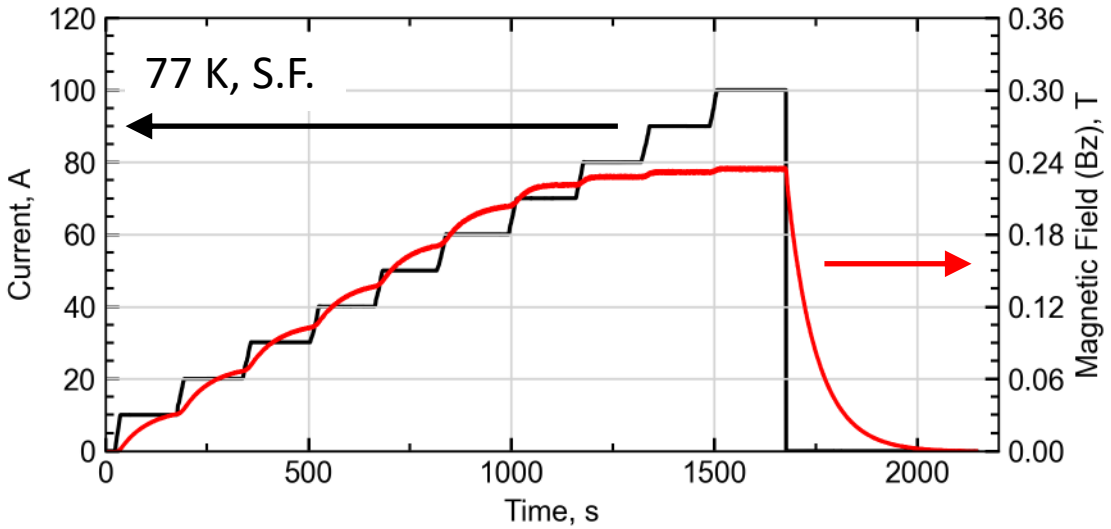
Pancake 1
cross-sectional view



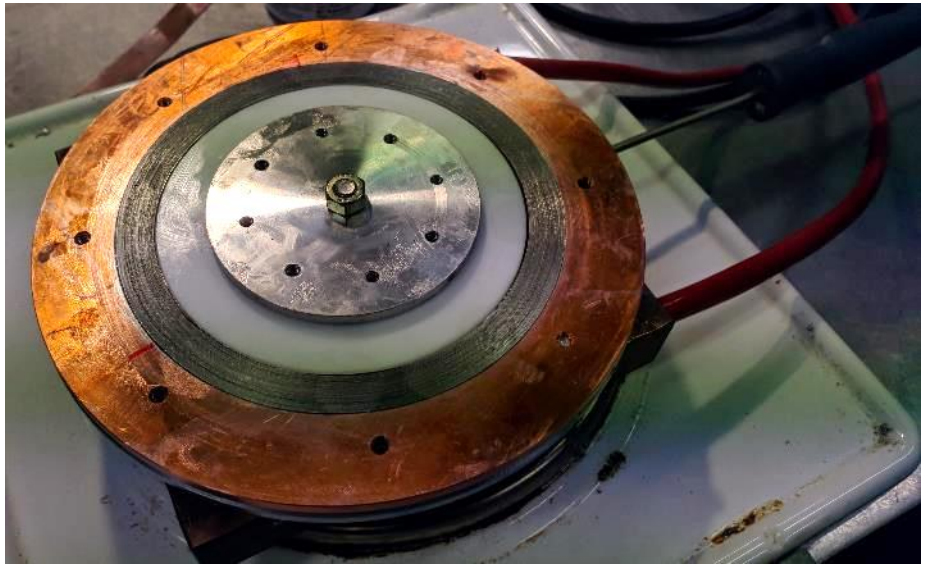
Soldering the coil-pack in an SnPb bath did not yield acceptable results.

Pancake 2 & 3: Electrical Performance at 77 K

- I_c criterions not reached (up to 100 A) as all coils were fully soldered (before machining).
- Small voltage slope appeared at I = 65 A -> Saturation of some turns (before machining).
- Overall coil I_c of 64 A expected (4.0 mm, 77 K, S. F., 100 µV/m) -> I_c of 60 A expected (after machining).
- Measured critical current of pancakes 2 & 3 were 65 A and 58 A after machining (after machining).
- Quench current of pancakes 2 & 3 were 75 & 65 A, stability of the coils decreased (after machining).
- No degradation due to machining and quenches without active quench protection.



Pancake 2 before machining, current steps up to 100 A

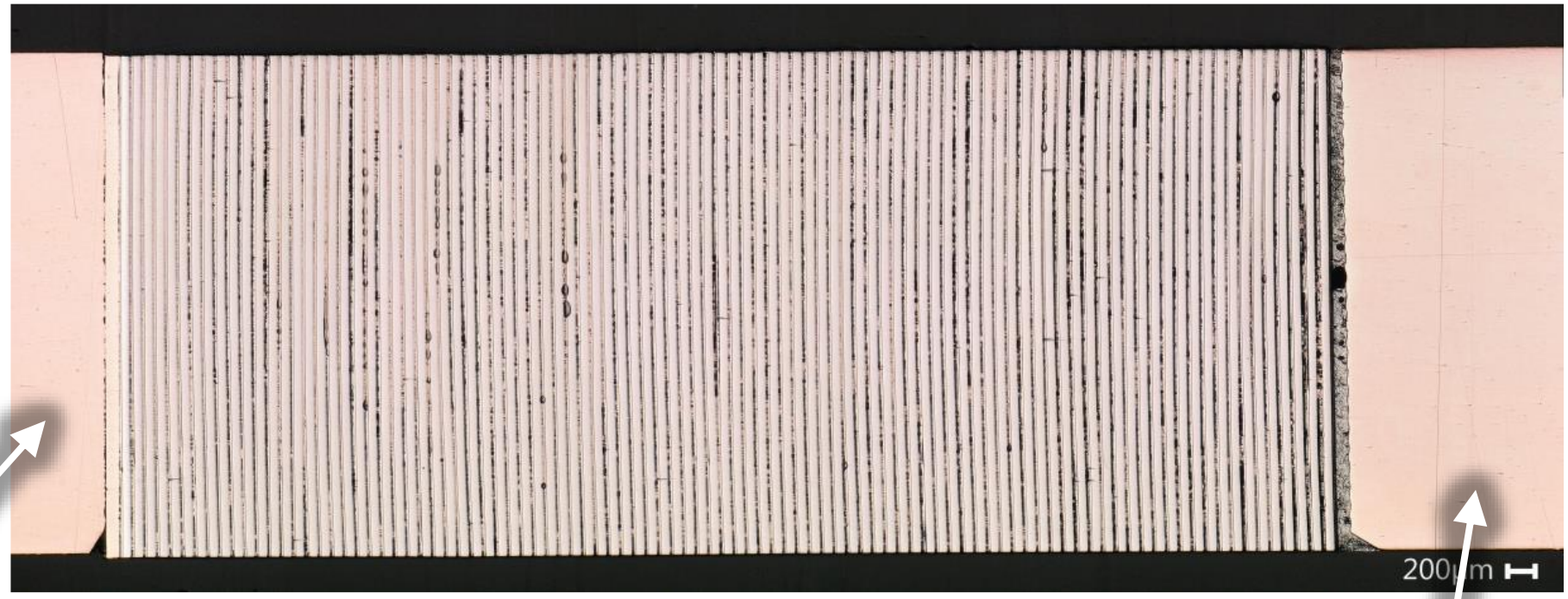


Soldering of the coil pack by manually adding alloy from top/bottom. Yielded good results conform expectation and requirements.

Cross-Sectional View of the Coil Pack

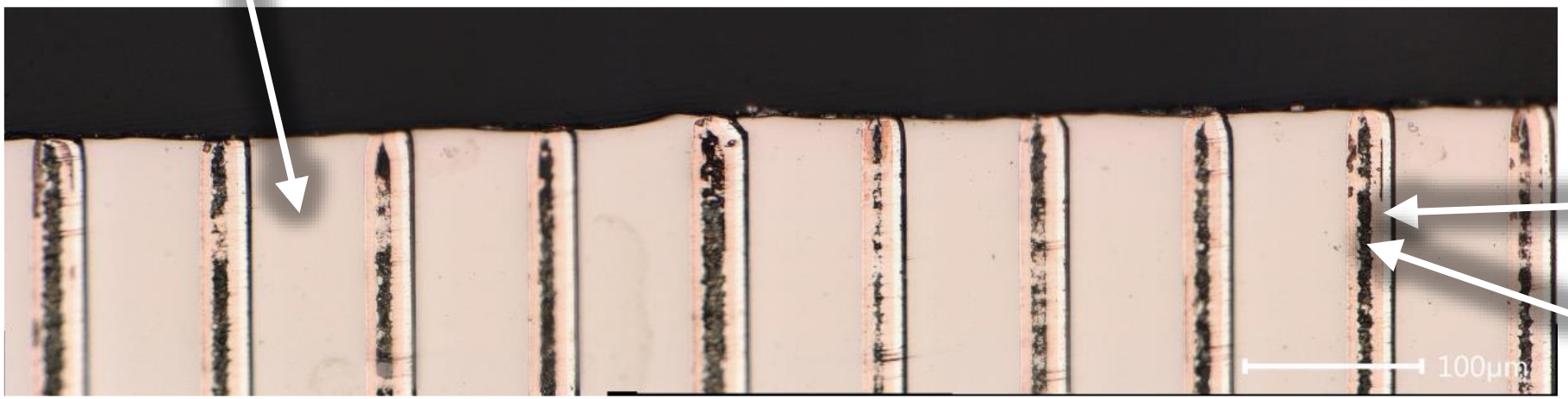
- **Pancake 2 & 3 had an overall good solder quality.**
- Machining provides a clear and clean cut.
- Differences in τ between P2 & P3 not explained by close-ups.

Pancake 2
cross-sectional view



Inner terminal
Hastelloy, 60 µm

Outer terminal



Surround copper plating, 5 µm

SnPb solder in between tapes, ~10 µm

Pictures by K. Buchanan, CERN

Conclusions

- A novel preparation procedure is developed to reduce the time constant of ReBCO HTS pancake coils.
- Three demonstrator NI HTS pancake coils were prepared according to this method.
- Their time constants were reduced by a factor 500-1000.
- No degradation observed due to soldering and machining for pancake 2 & 3.
- Good value of coil resistance in between fully soldered and fully insulated, while maintaining a good level mechanical- and thermally stability.
- Radial resistance may be further controlled by only partially removing the copper edge and leaving some radial strips intact or by adding a thin metal film on the sides.

Preparation technique is promising for magnets which require fast charging and discharging.