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Towards ReBCO 20T+ Dipoles for Accelerators

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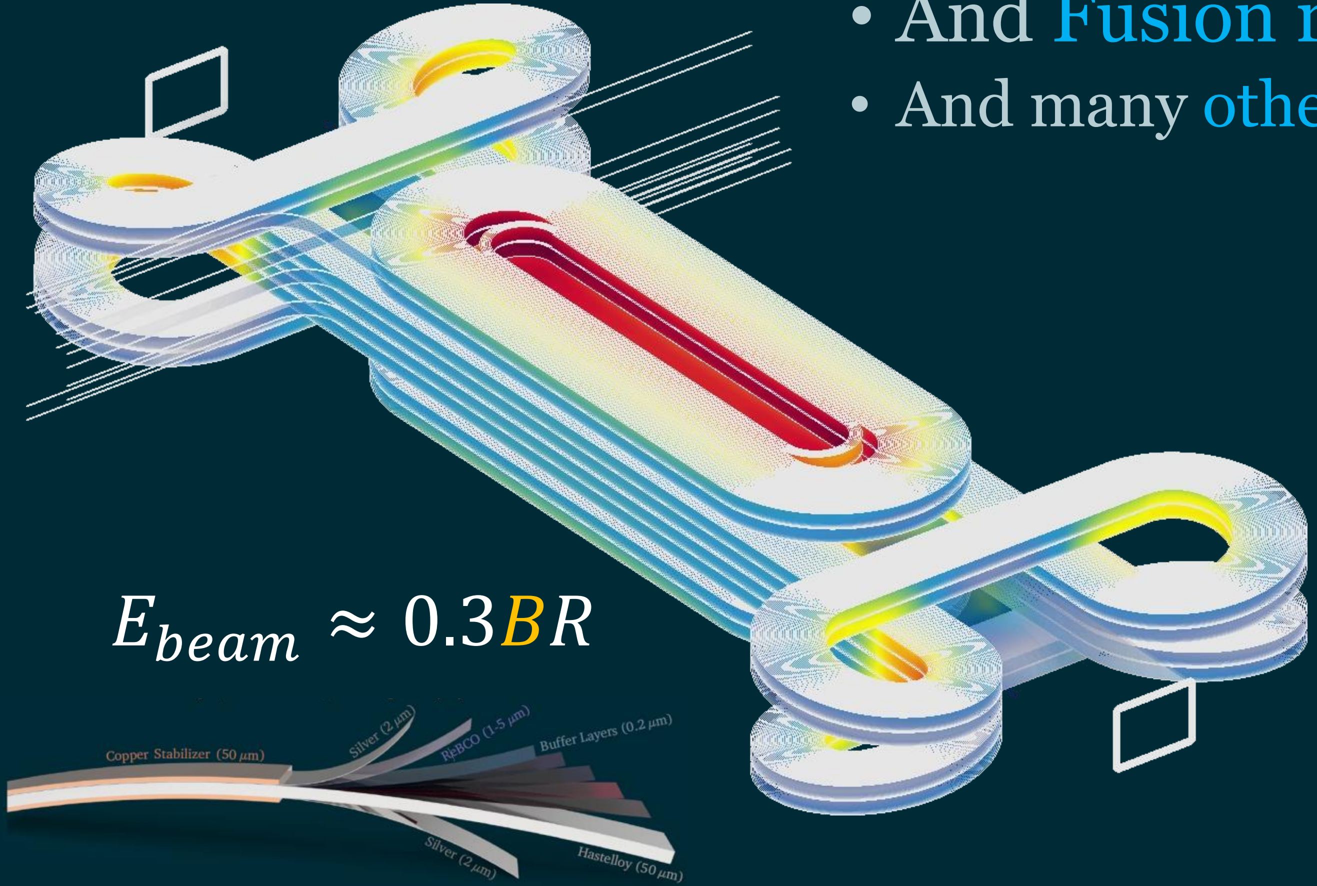
EuCARD² CERN

I believe REBCO HTS is THE superconducting material for future high field magnets …

- For particle accelerators (di-, quadpoles)
- And Fusion reactors (toroids)
- And many other applications!

Plots with Field2017



$E_{beam} \approx 0.3BR$

$RR \propto B^4$

We are hungry for magnetic field …

Why?

Stability of HTS Conductor illustrated

Quenching LTS wire
100 µJ

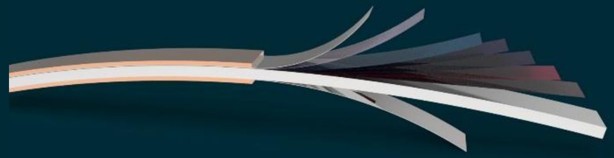
0.1 g
pin

10cm

Quenching an HTS Tape
100mJ

apple

10cm



Quenching an HTS cable
1J+
(depends on geometry)

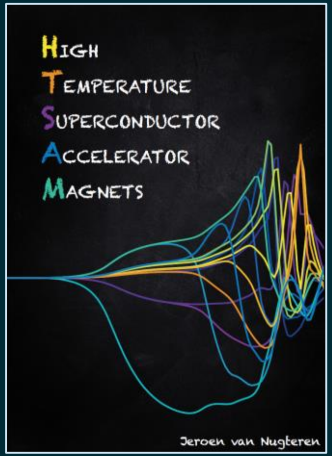
cannon ball

10cm

- It has a high current density up to very high magnetic fields and moderate temperature
- It has a very high quench energy and is thus super stable
- Robust and relatively Easy to handle (no heat treatment)

The Feather-M2.1-2 (SuperOx, Sunam)

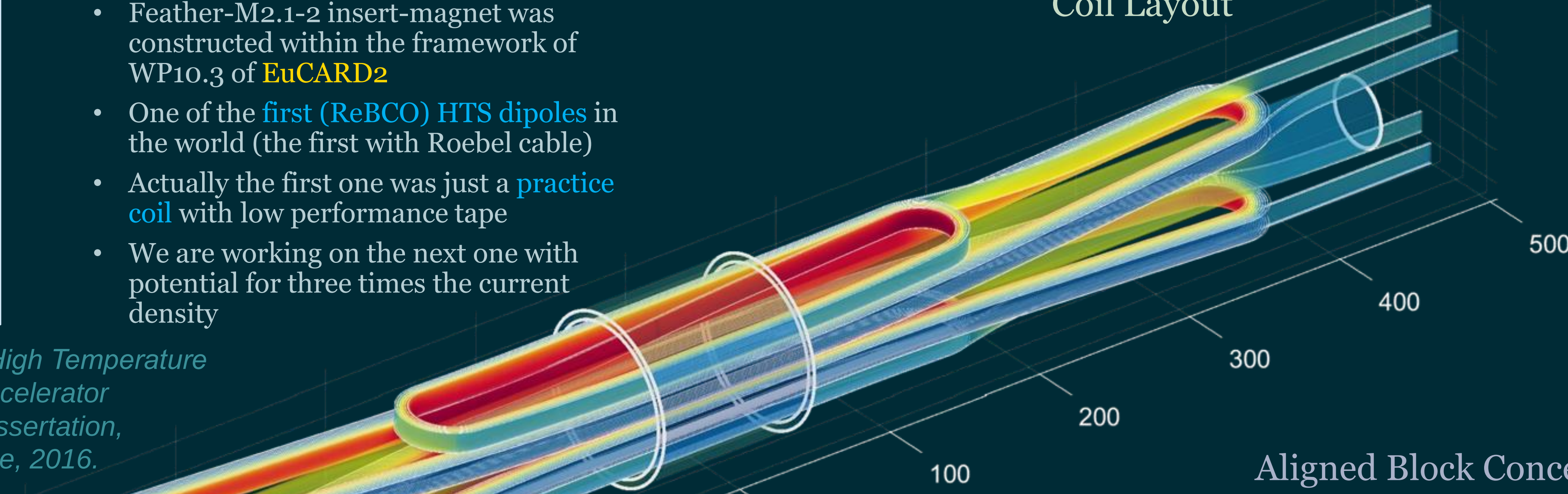
Research Thesis



- To develop HTS magnets:
  - Feather-M2.1-2 insert-magnet was constructed within the framework of WP10.3 of EuCARD2
  - One of the first (ReBCO) HTS dipoles in the world (the first with Roebel cable)
  - Actually the first one was just a practice coil with low performance tape
  - We are working on the next one with potential for three times the current density

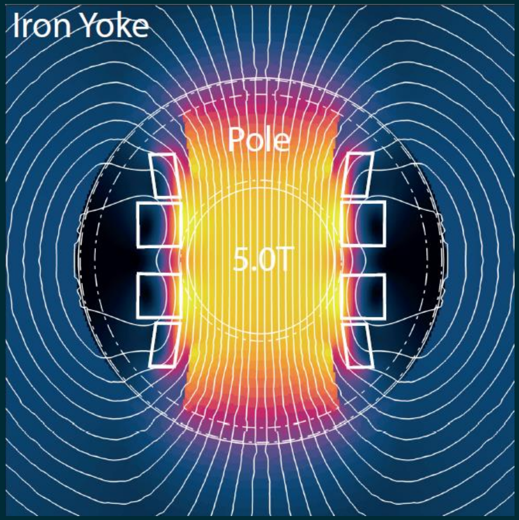
J. van Nugteren, "High Temperature Superconductor Accelerator Magnets," Ph.D. dissertation, University of Twente, 2016.

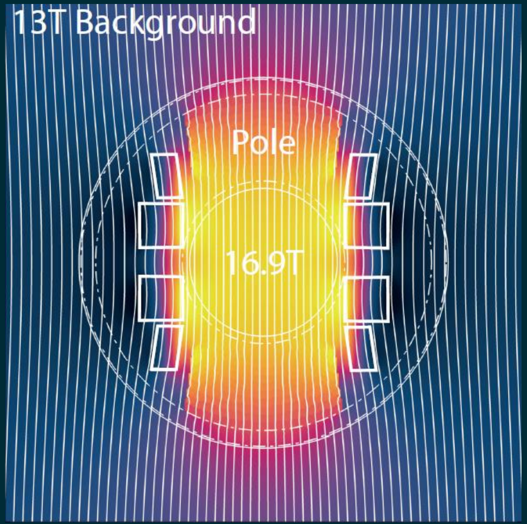
Feather-M2 Insert-Magnet Coil Layout



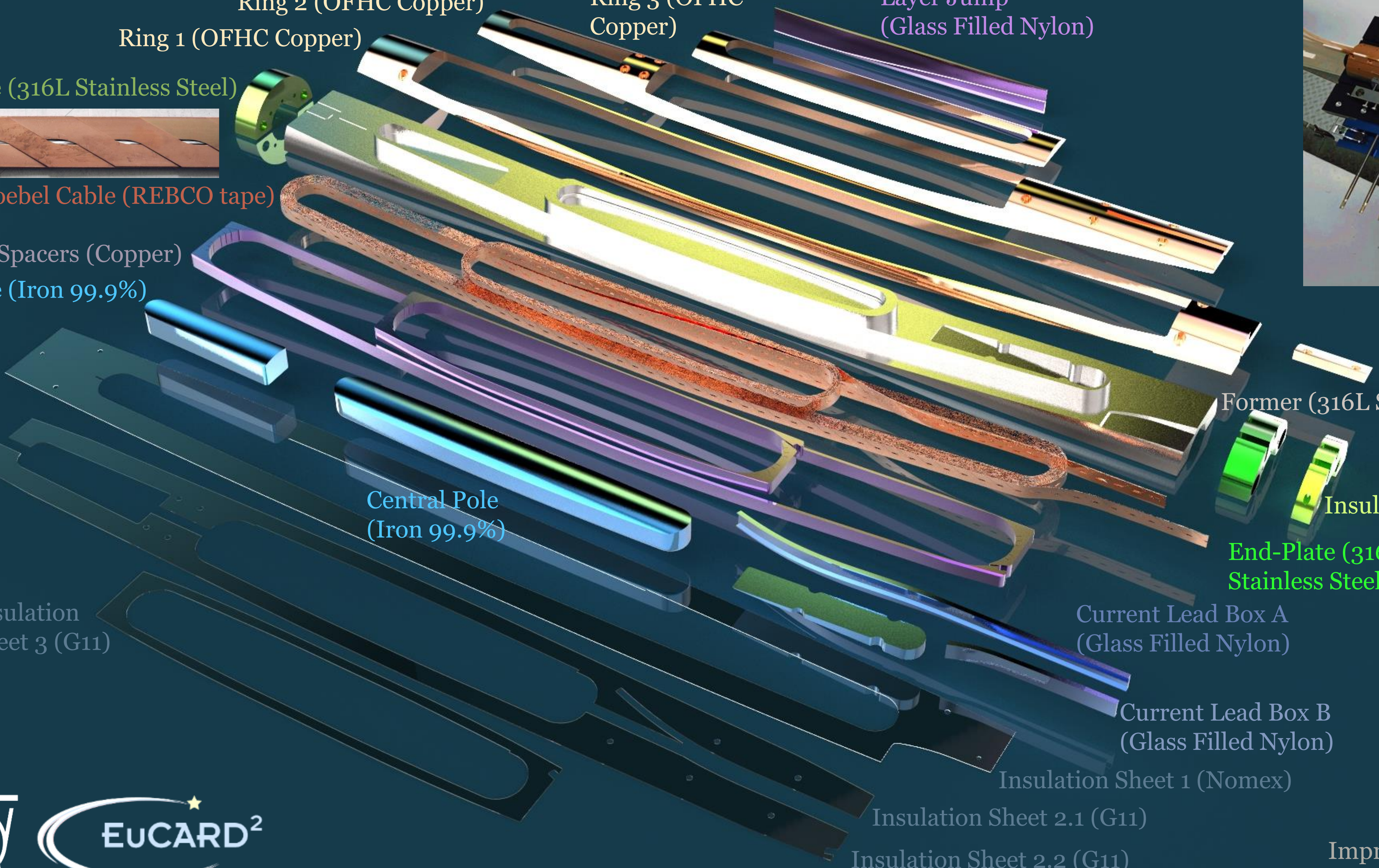
Roebel Cable (REBCO tape)

Aligned Block Concept





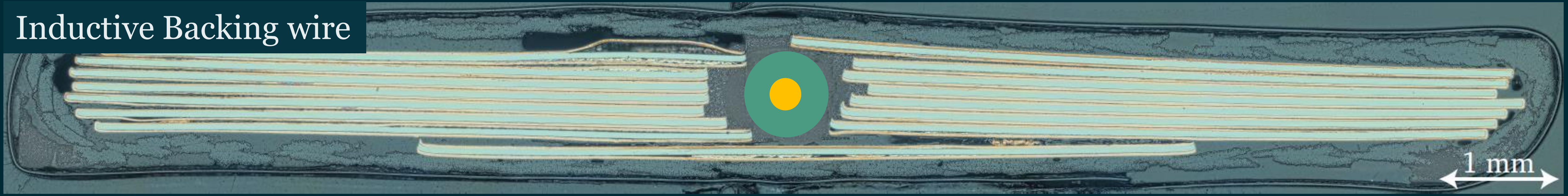
Winding, Impregnation and Assembly I

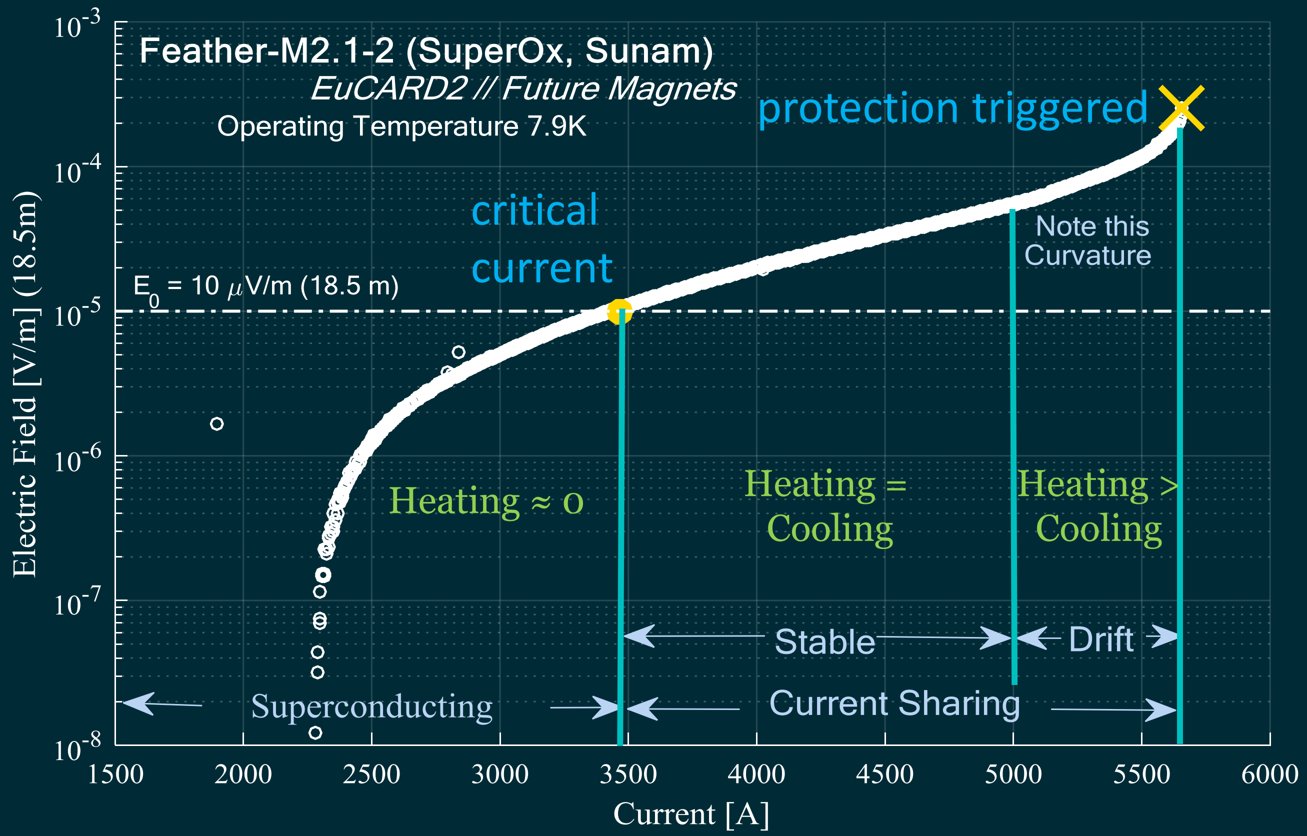


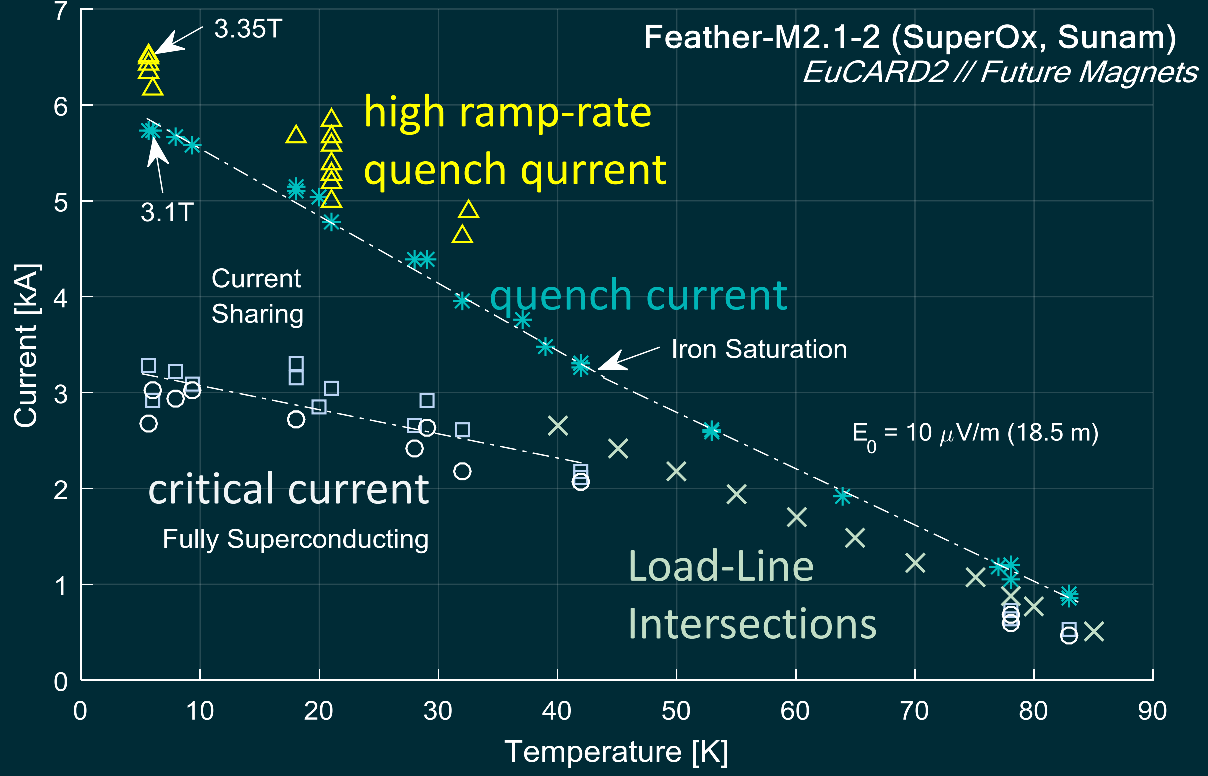
Coil Winding

Impregnated Dummy With CTD 101K

Superconducting Transition

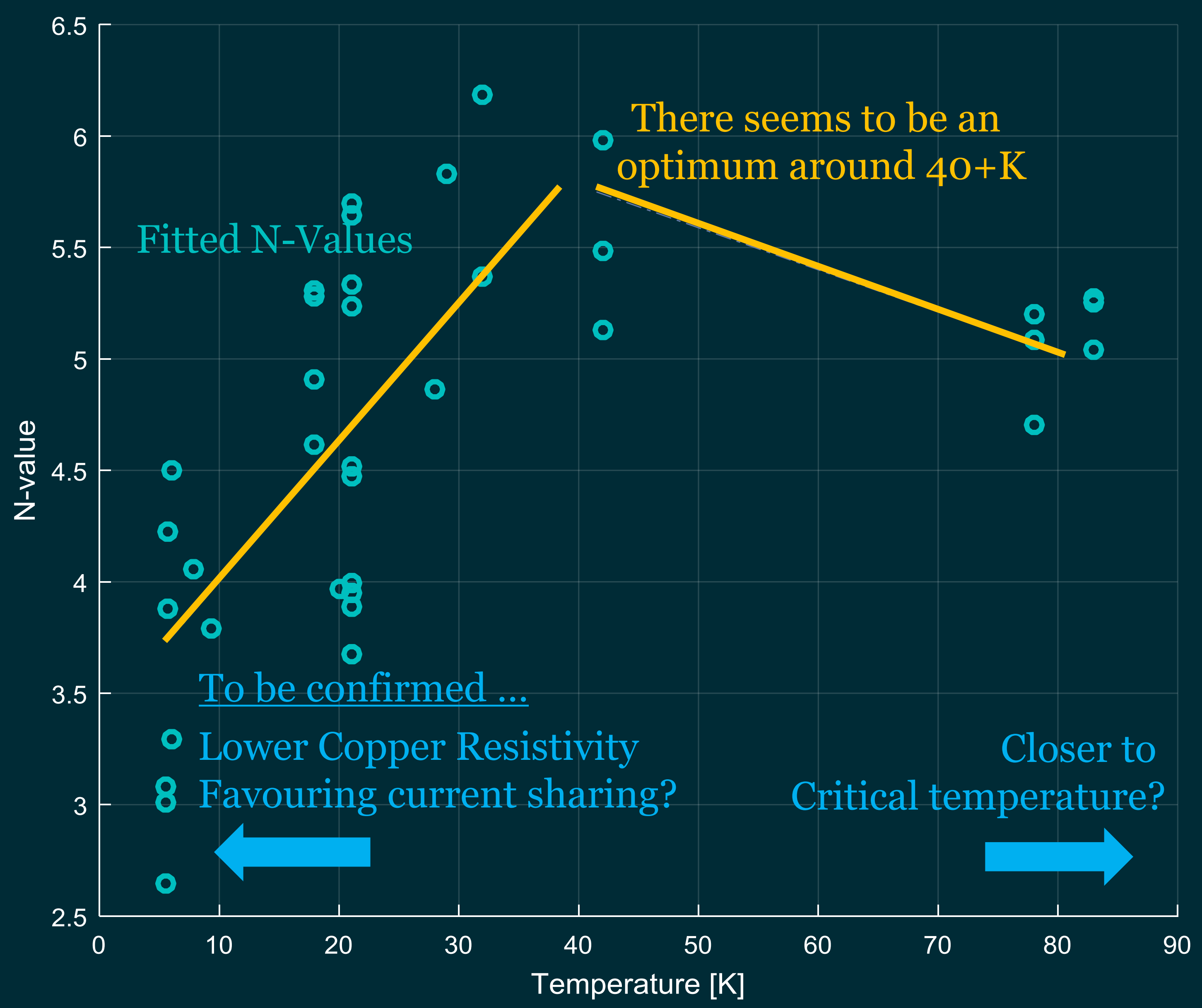




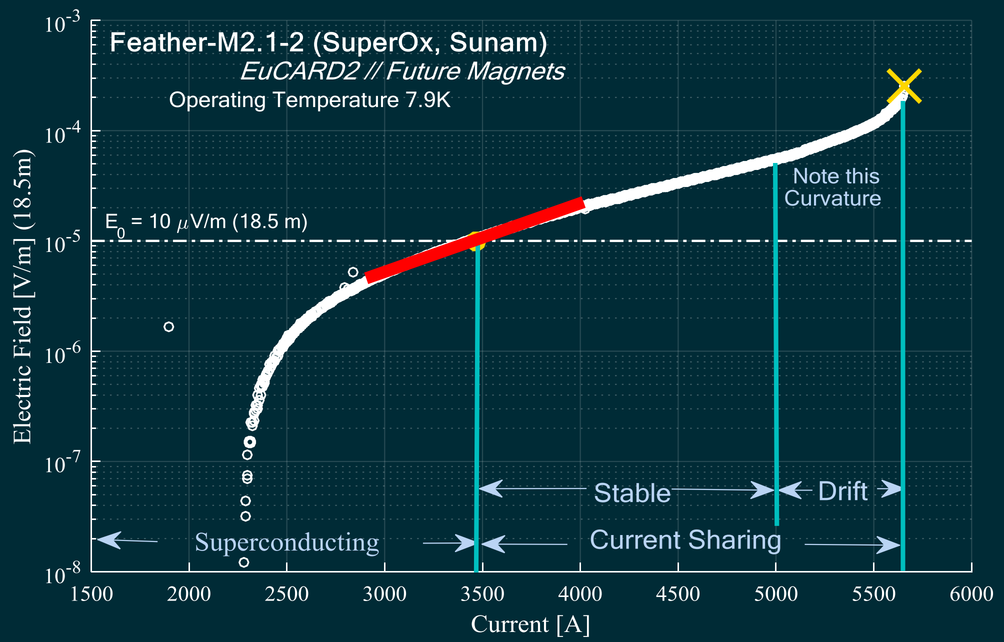


- 160% difference between critical current at 10 μV/m and quench current

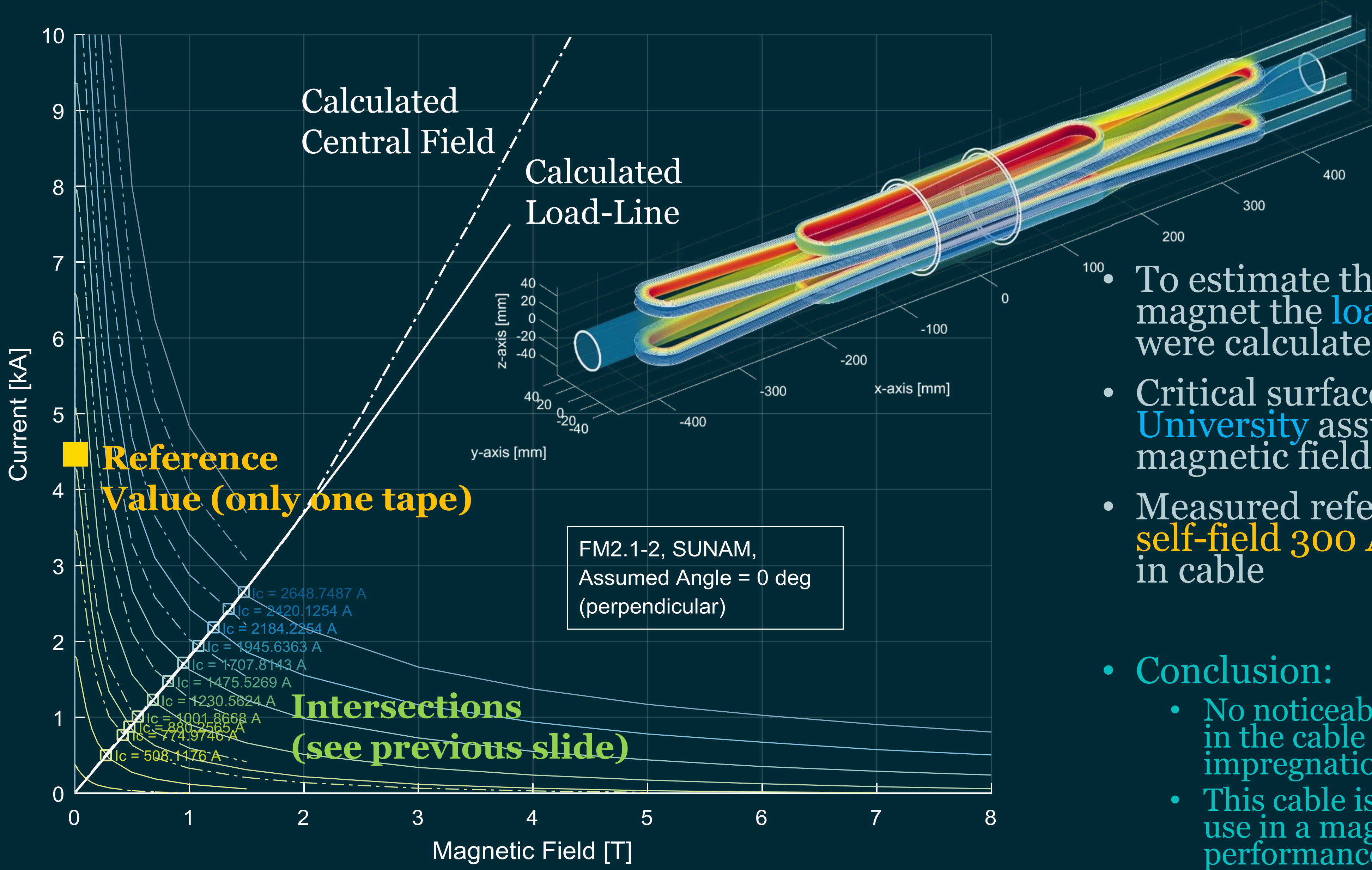
Measured N-Values



- The N-values were determined by fitting the power law to the measured electric field versus current
  - $E = E_0 \left[\frac{I}{I_c}\right]^N$
- In Essence it is the slope on log-log plot near the critical current
- N-values are very low. Likely an effect of current sharing and joint resistance



Load-Line Intersections



Feather-M2

Magnetic Model

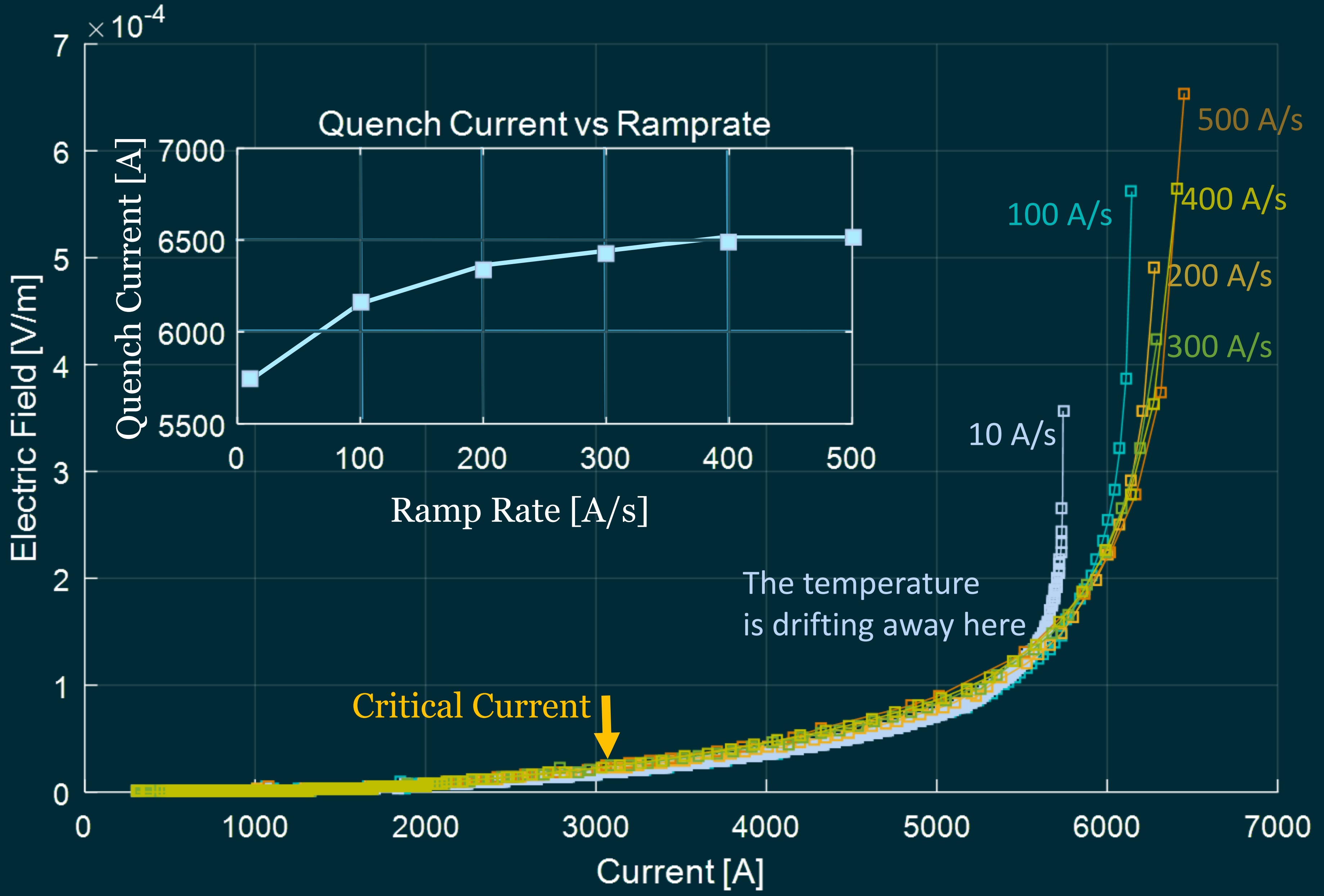
- To estimate the performance of the magnet the load-line intersections were calculated
- Critical surface from Victoria University assumed perpendicular magnetic field
- Measured reference value at 77 K self-field 300 A per tape 15 tapes in cable

- Conclusion:
  - No noticeable degradation occurred in the cable during winding, impregnation and assembly
  - This cable is not very suitable for use in a magnet. Much better performance on next magnet

Superconducting Transition and Ramp-Rate

- Quench current increases when ramped fast
- Essentially we are skipping the drift regime
- Opposite result from LTS where coupling losses reduce the quench current
- HTS has much more margin and seems to be unaffected by coupling loss

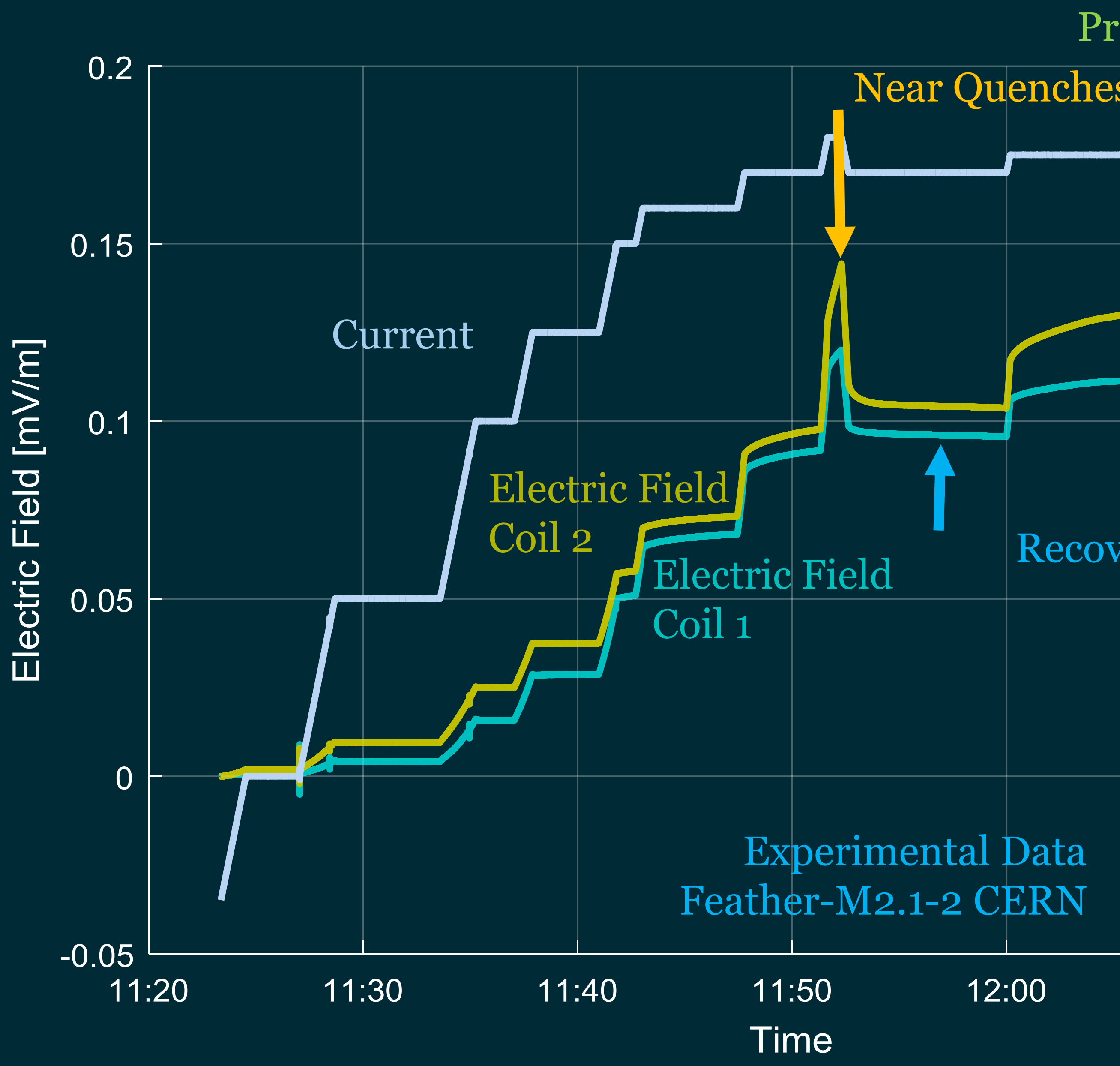
- Conclusion
  - The drift region implies temporal effects with respect to the quench current

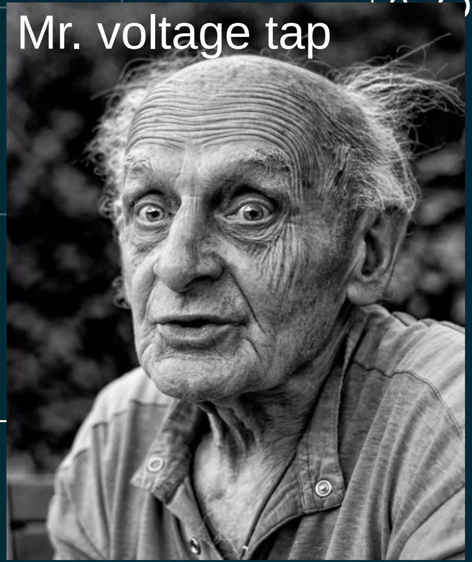


Detecting the Onset of a Quench I (electric field)

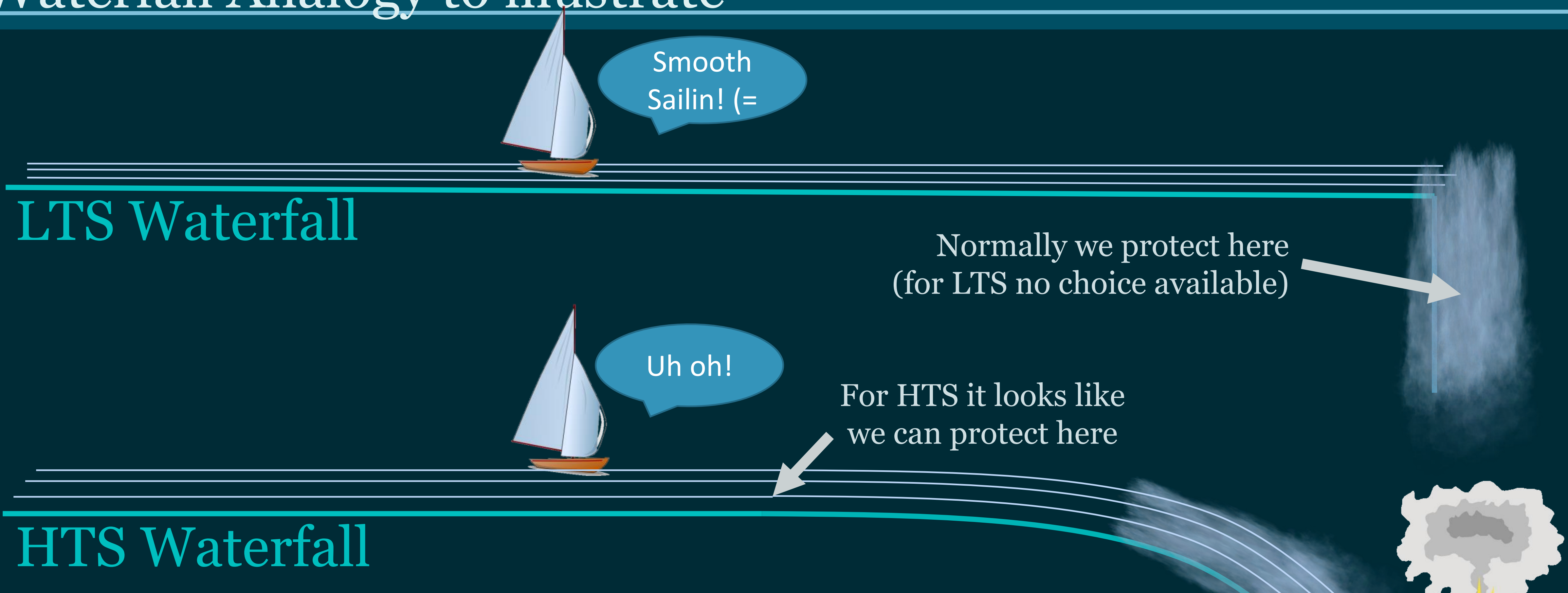
- Drift in the electric field is a clear indication that the magnet is about to quench
- If not ramped fast, the electric field starts drifting minutes ahead of time
- Reduction of only 100 A results in immediate recovery!

- Conclusion
  - If this behaviour is also present in higher current density magnets this could be a viable method for protecting future HTS magnets



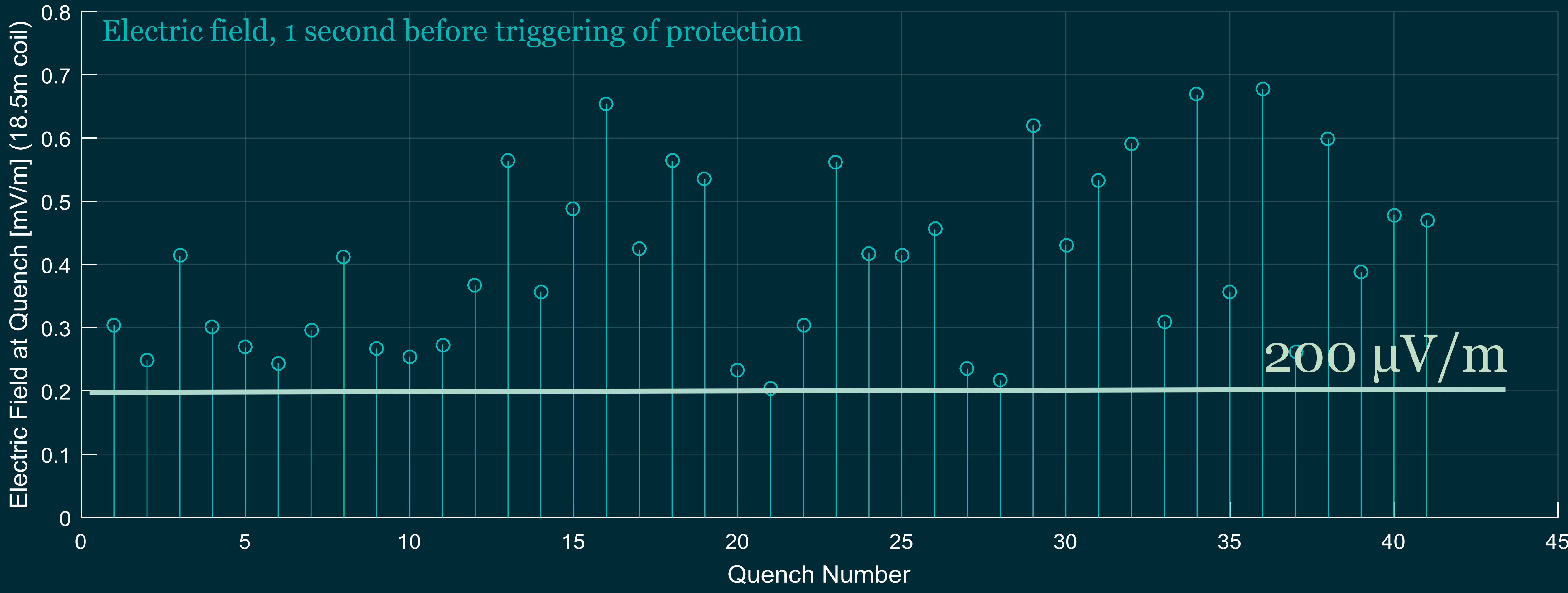


Waterfall Analogy to illustrate



- This is very different from experiences from other groups and we think the following is of importance here (further investigation needed):
  - We used a cable allowing the current to redistribute smearing out the resistive power dissipation throughout the coil
  - We operated the magnet in force flow helium gas reducing cooling (this is the motor of the boat)
  - We were measuring microvolts by using a low sampling frequency and inductive backing wire (3 Hz)

Detecting the Onset of a Quench II (electric field)

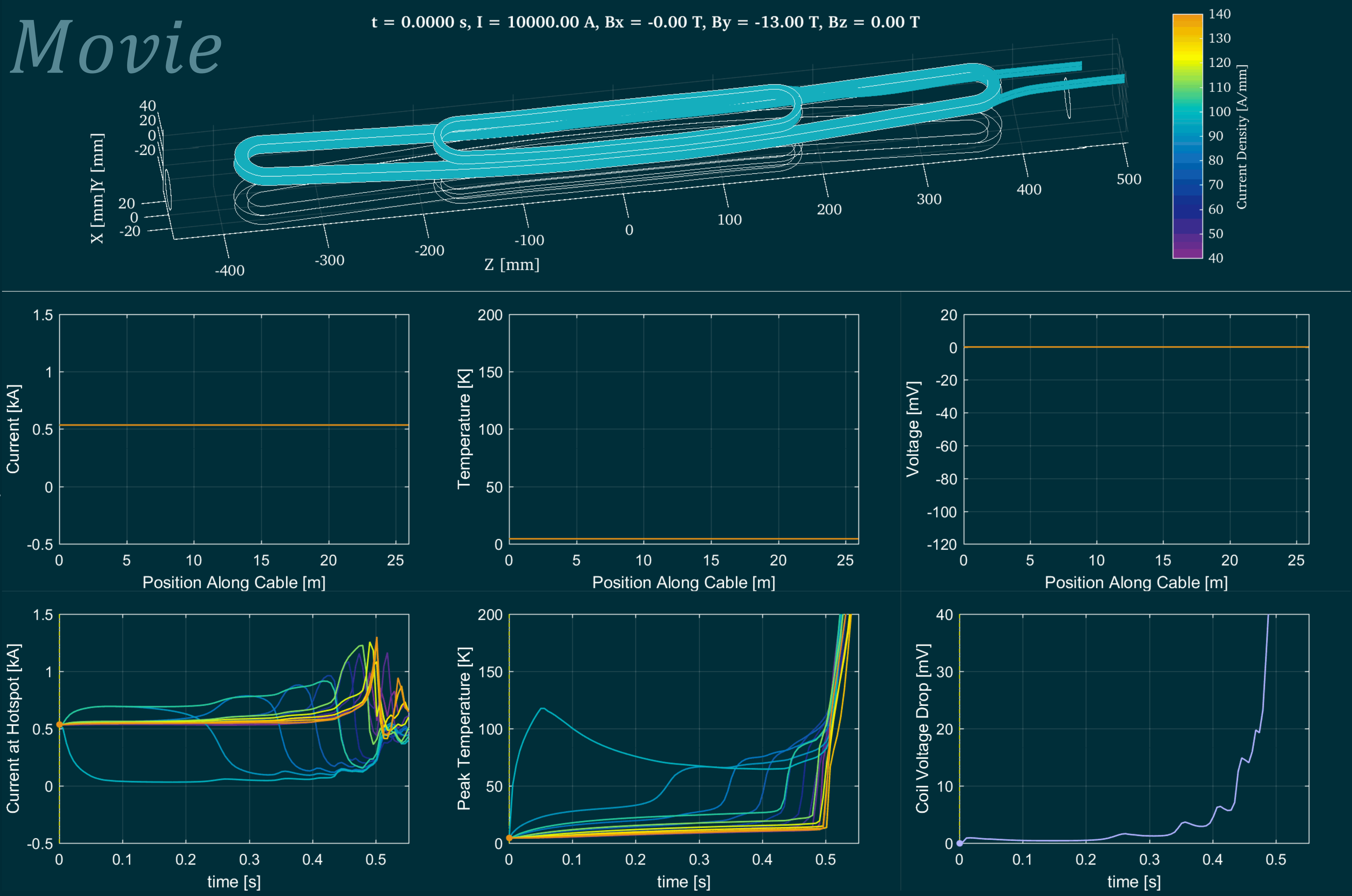


- All quenches occur over an electric field of 200 μV/m
- Only quenches due to exceeding critical current

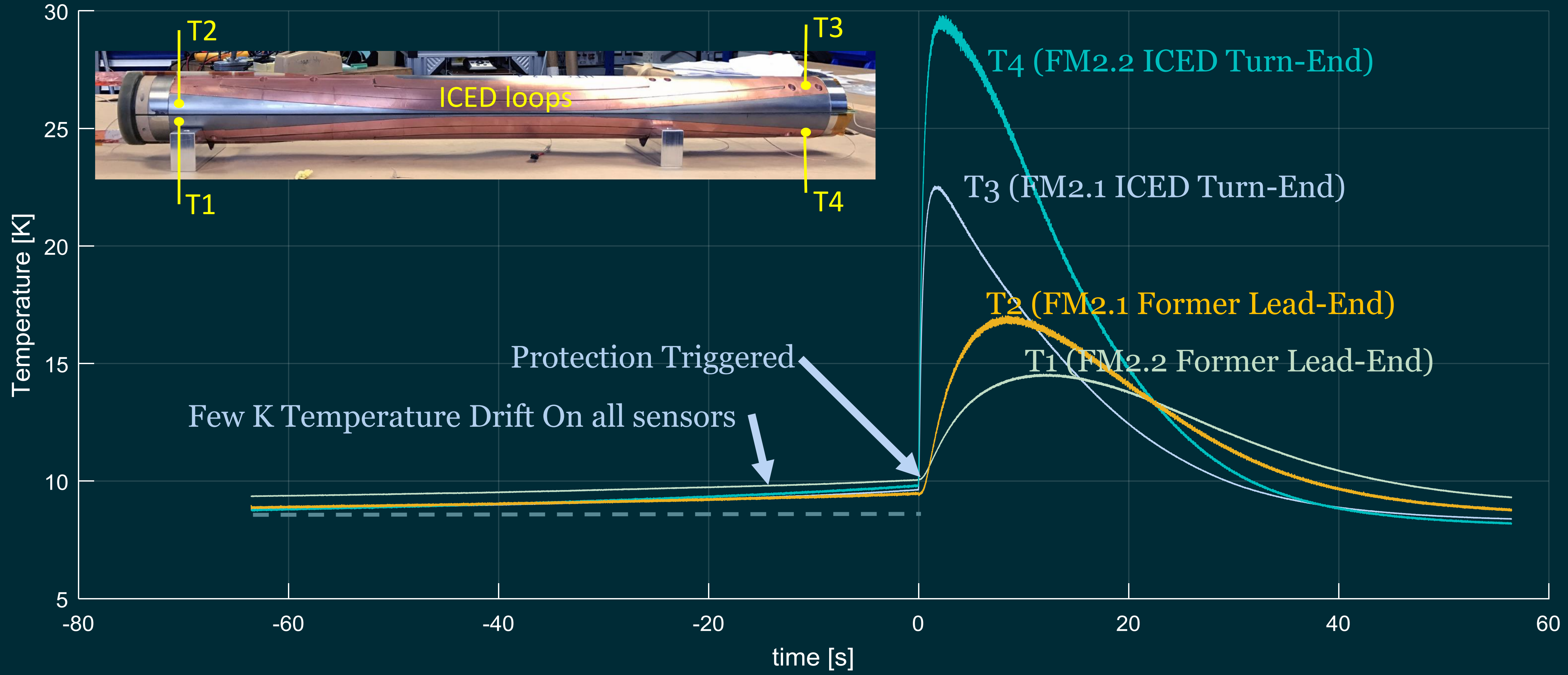
- Conclusion
  - No unexpected quenches due to cracking of resin, flux jump, training etc.

"Fast" Quenches

- Predicted by ELMATH code (developed by me)
- So far no "fast" single tape quenches or avalanche effect observed
- Not enough local power deposition
- Pick-up coils are dead silent



Detecting the Onset of a Quench III (temperature sensors)



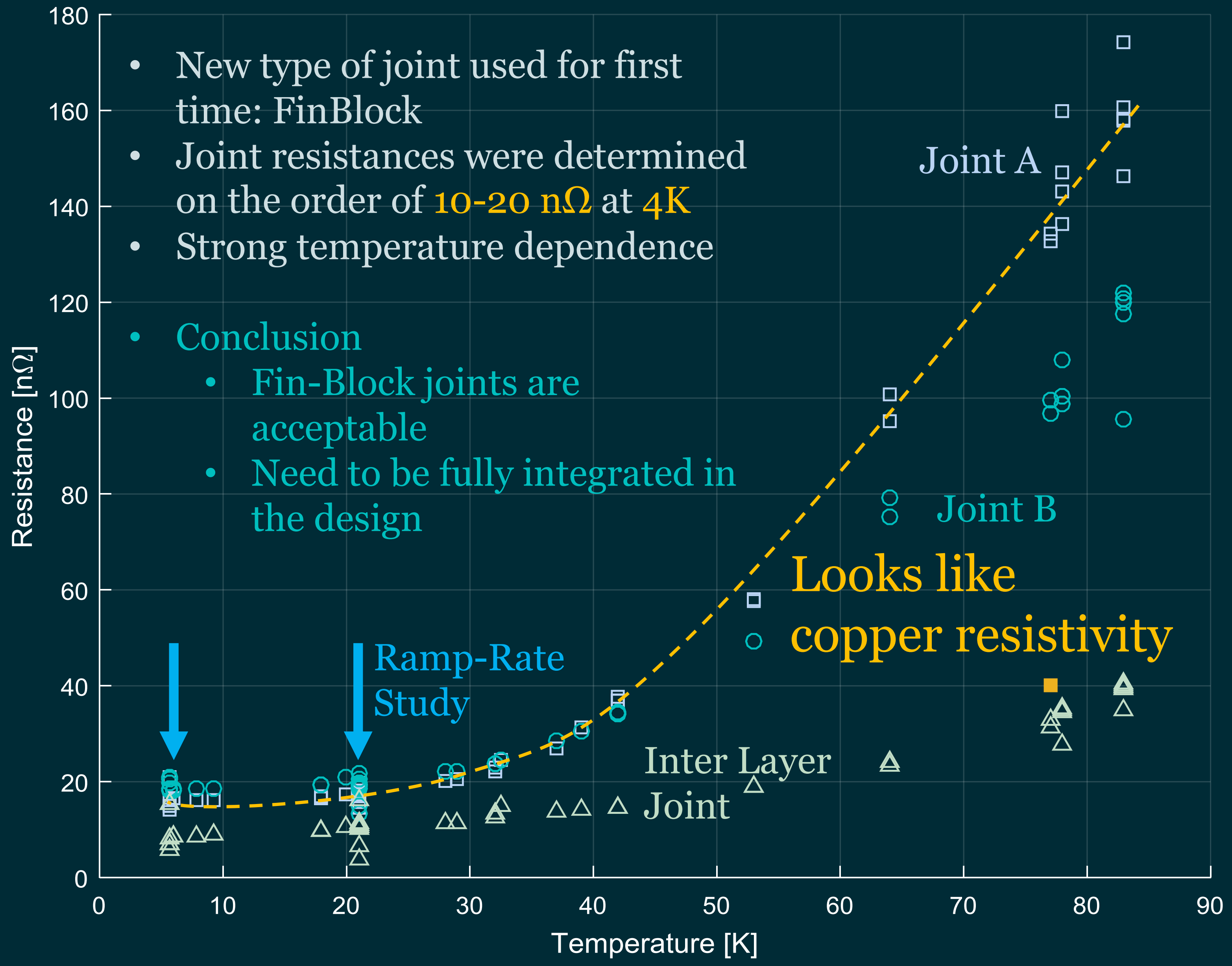
- Temperature drifts away before quench
- Having distributed temperature sensing (i.e. temperature map of the coil) should yield interesting results when magnet is in current sharing regime

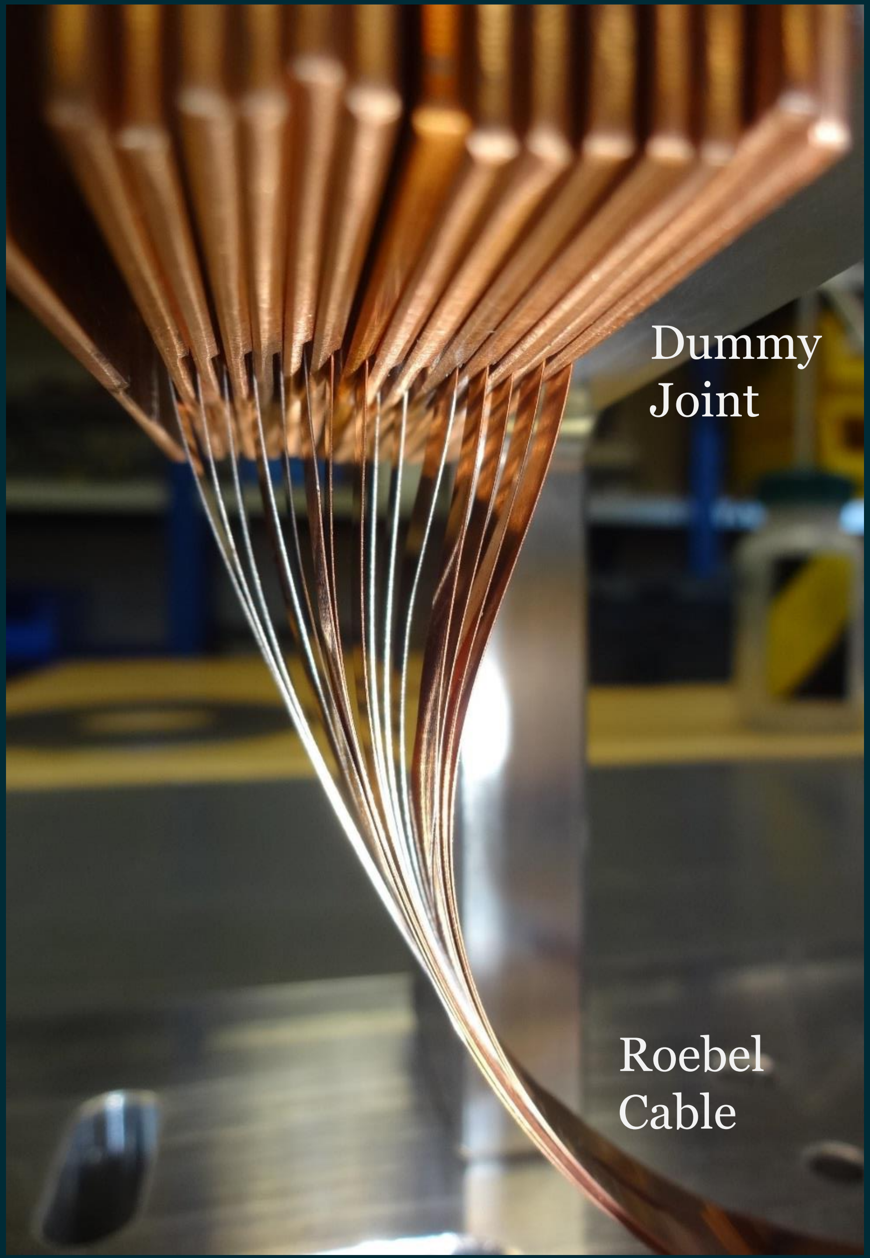
- Conclusion
  - Onset of quench also visible on temperature sensors

Joint Resistances (fin-block)

- New type of joint used for first time: FinBlock
- Joint resistances were determined on the order of 10-20 nΩ at 4K
- Strong temperature dependence

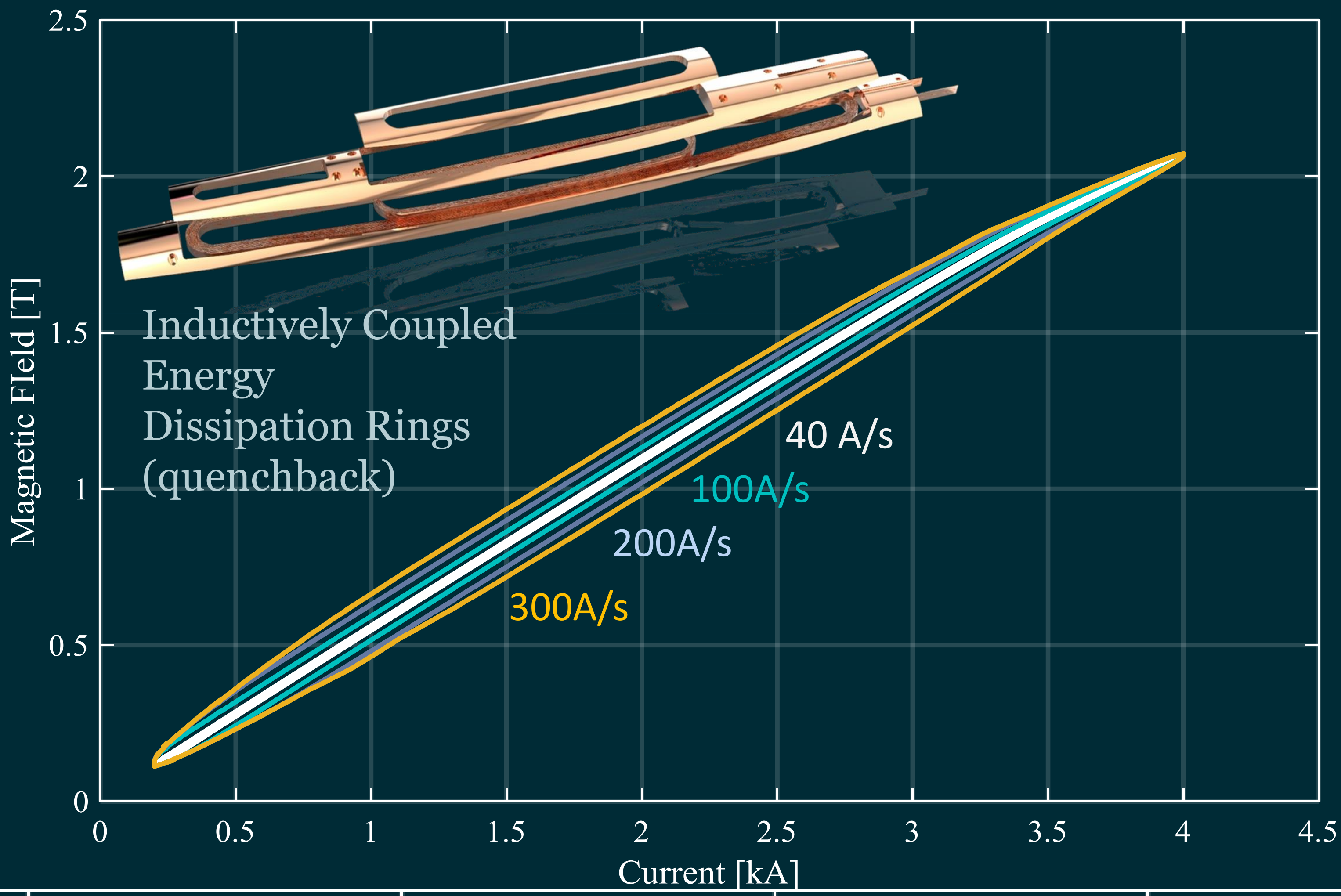
- Conclusion
  - Fin-Block joints are acceptable
  - Need to be fully integrated in the design

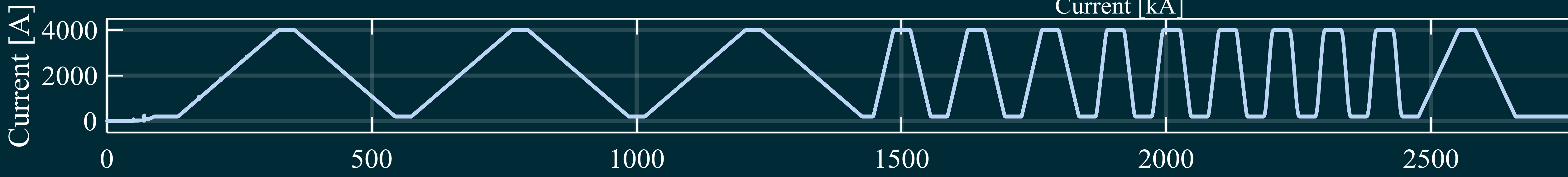




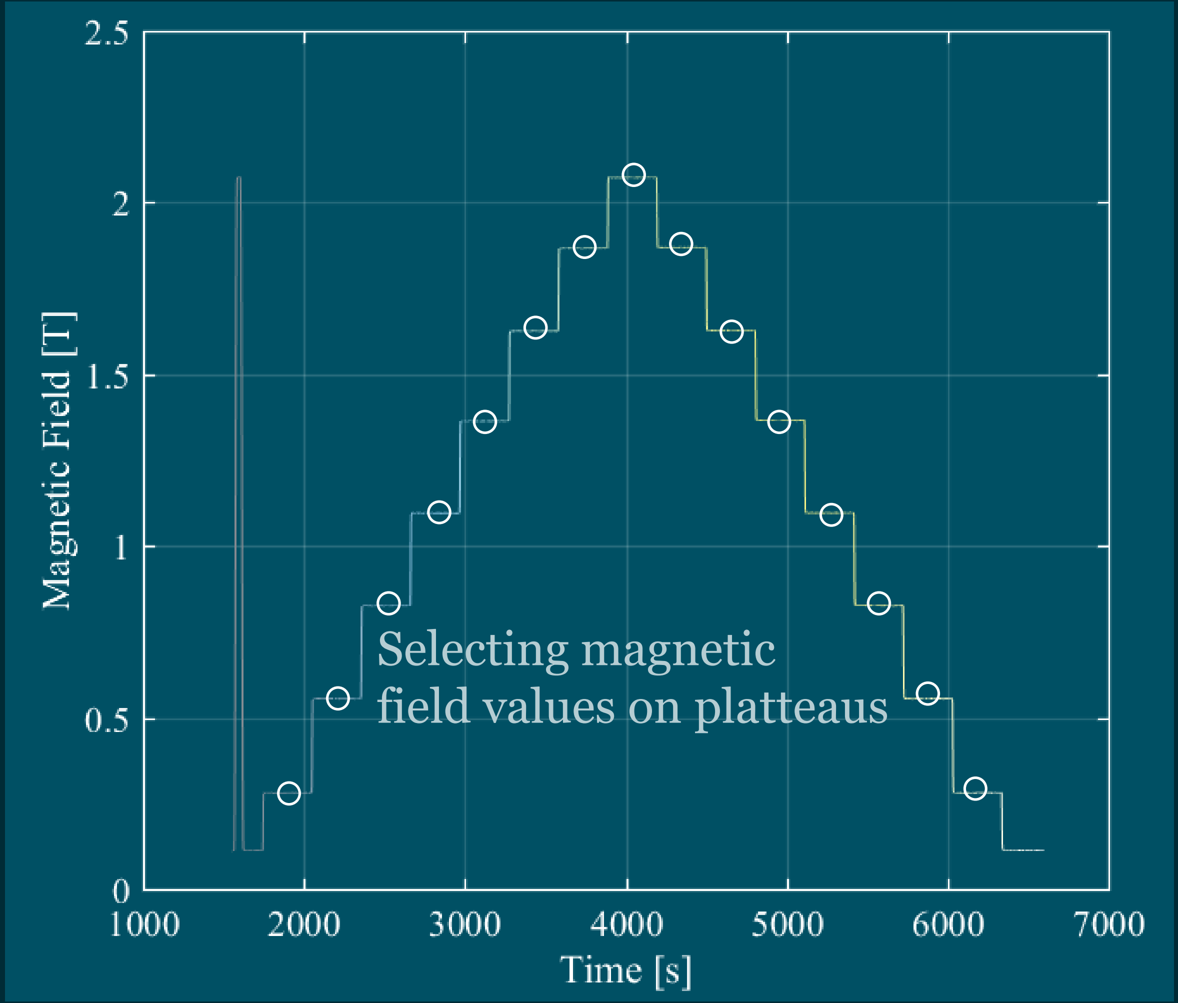
Magnetic Measurements I (resistive effect)

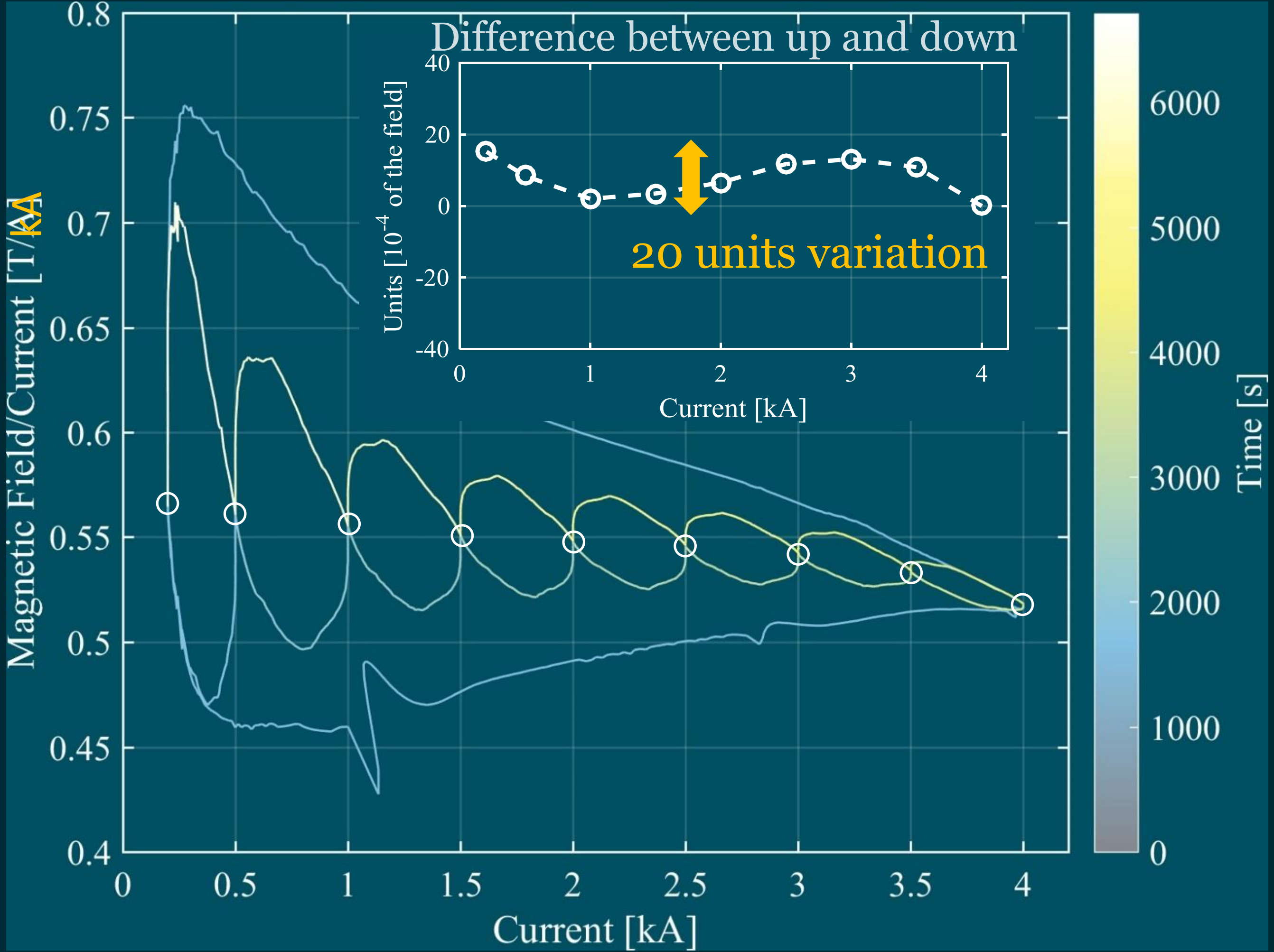
- Magnetic field in aperture was measured using Hall effect sensors
- Hall sensors were cross-calibrated with pick-up coils
- The hysteresis (lagging behind) of the magnetic field with the transport current strongly depends on ramp-rate
- This is likely the current induced in the copper ICED ring due to the time-changing magnetic field
  - i.e. the ring tries to resist a change of magnetic field
  - Actually appears as coupling due to its frequency dependence
- More on this effect in EUCAS 2017 by Carlo Petrone





Magnetic Measurements II (persistent current effect)



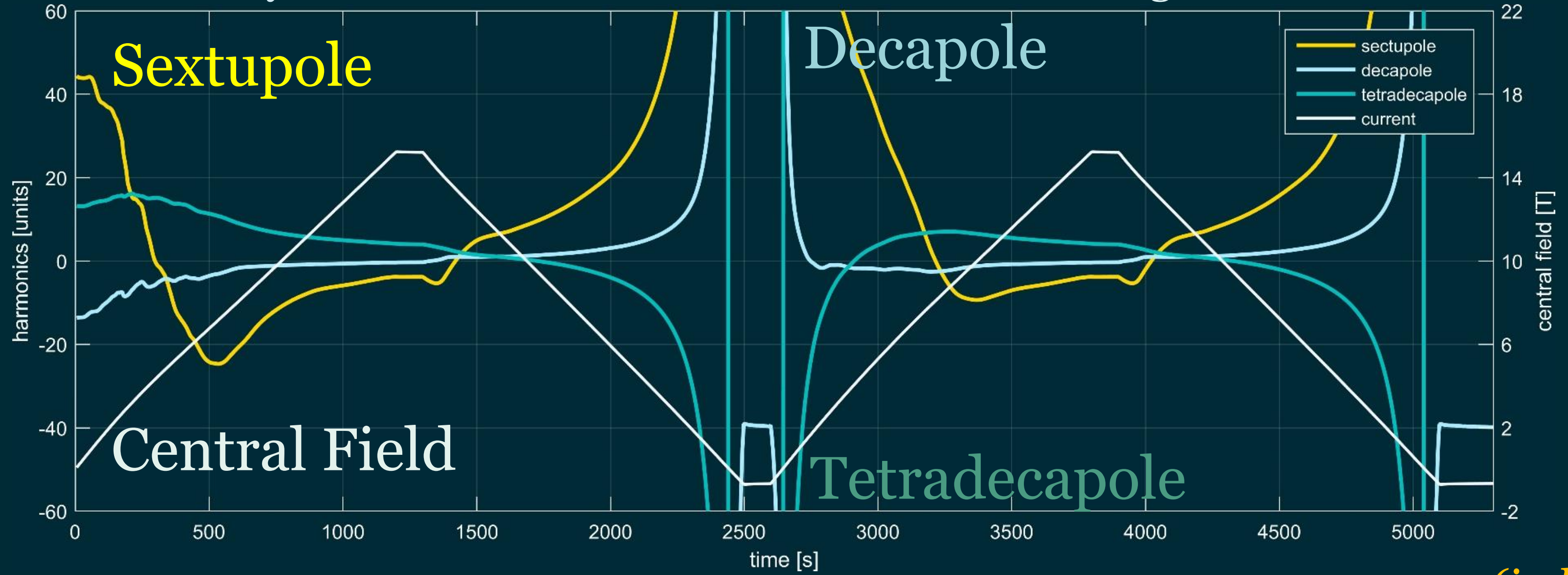


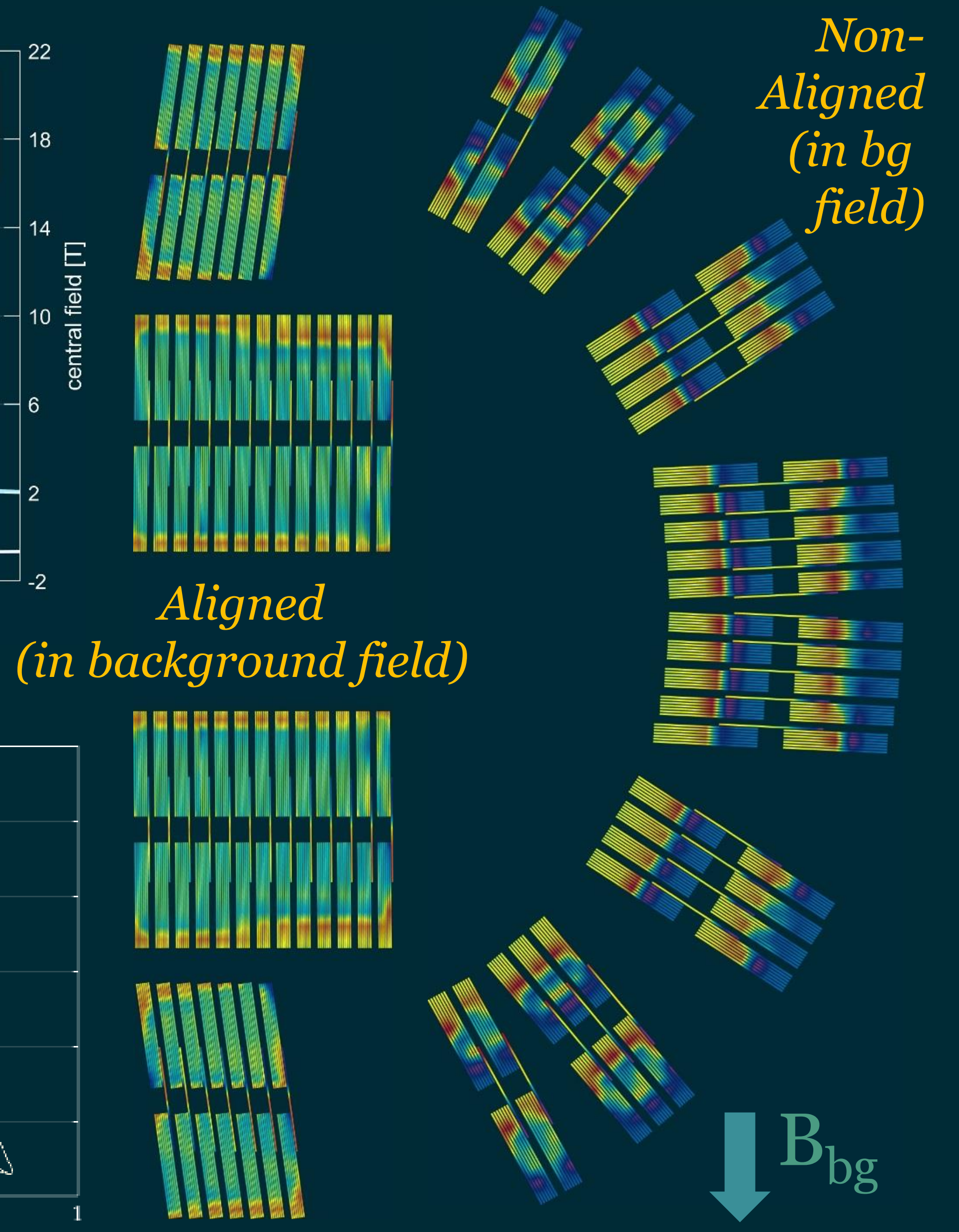
- To measure only steady state effects a staircase ramp was performed
- The acceleration and deceleration of the power supply give interesting pearl necklace effect
- Difference between ramping up and down is persistent current effect
- Only 10 units variation, likely due to the alignment of the field by the iron

- Conclusion
  - Only 10 units variation due to persistent currents
  - More on this in EUCAS 2017 by Carlo Petrone

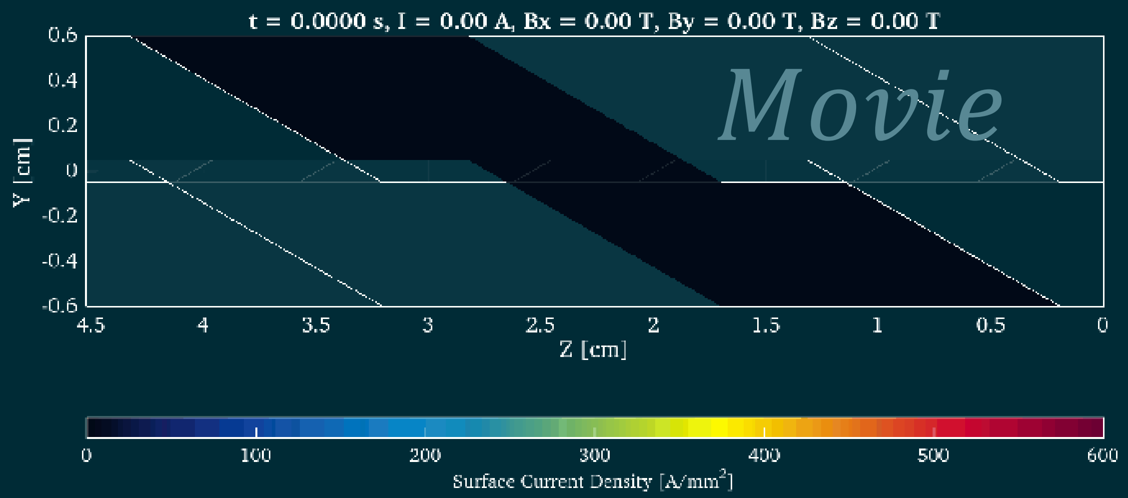
What Causes Persistent Current Effects?

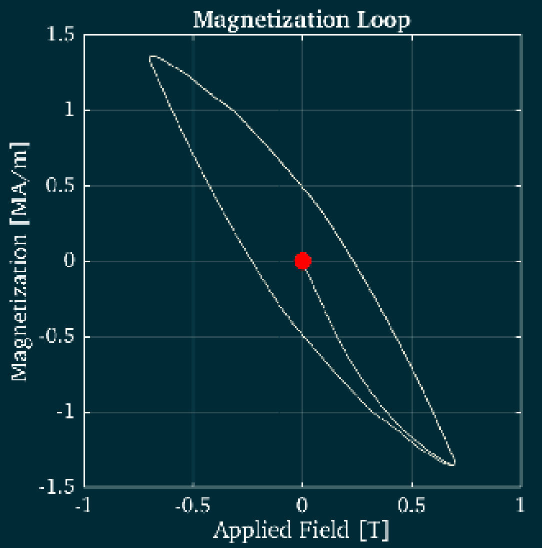
Calculated Dynamic Harmonics for Cosine Theta (non aligned)





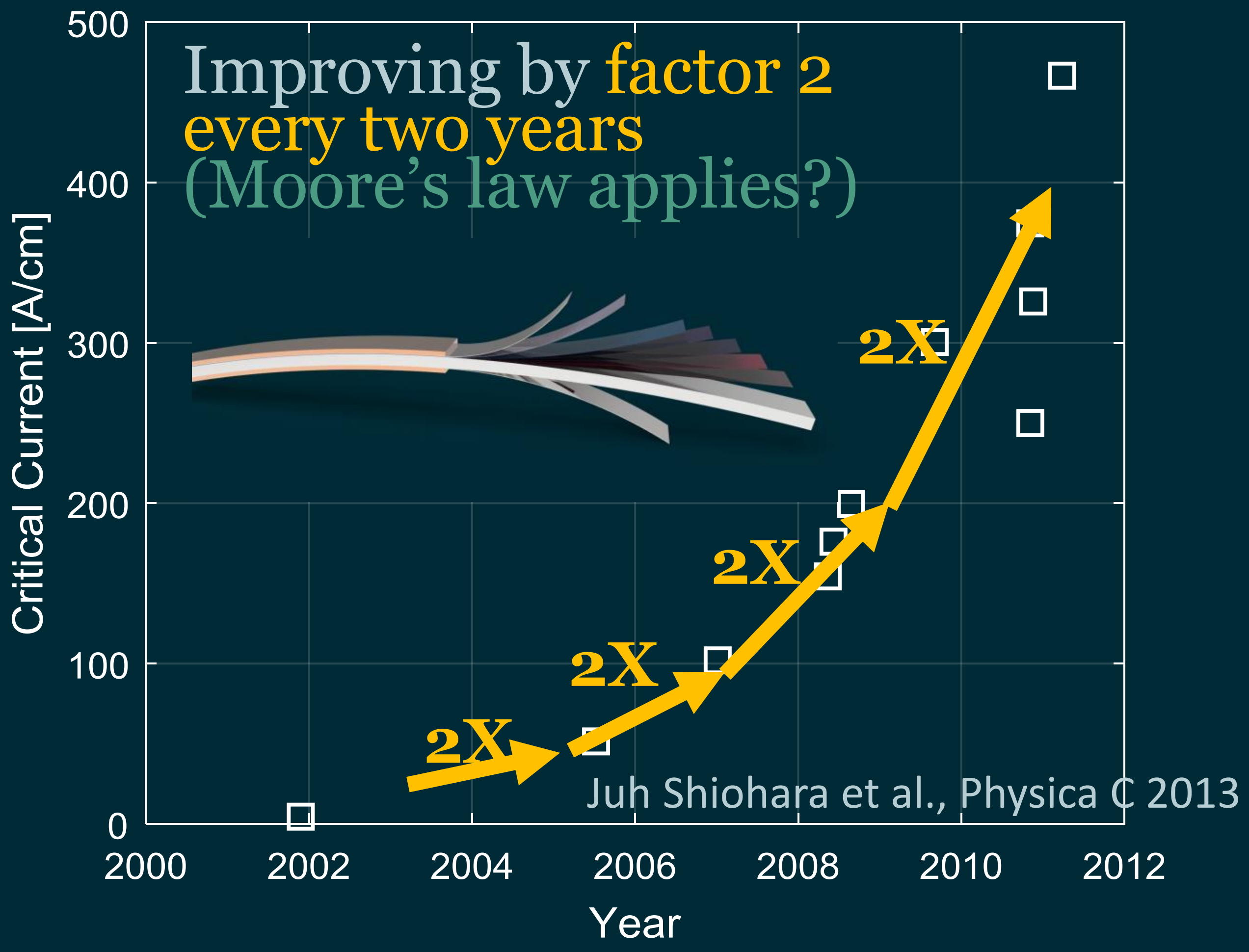
Calculated Magnetisation Currents in Roebel cable





The Next Feather-M2 (and improving conductor)

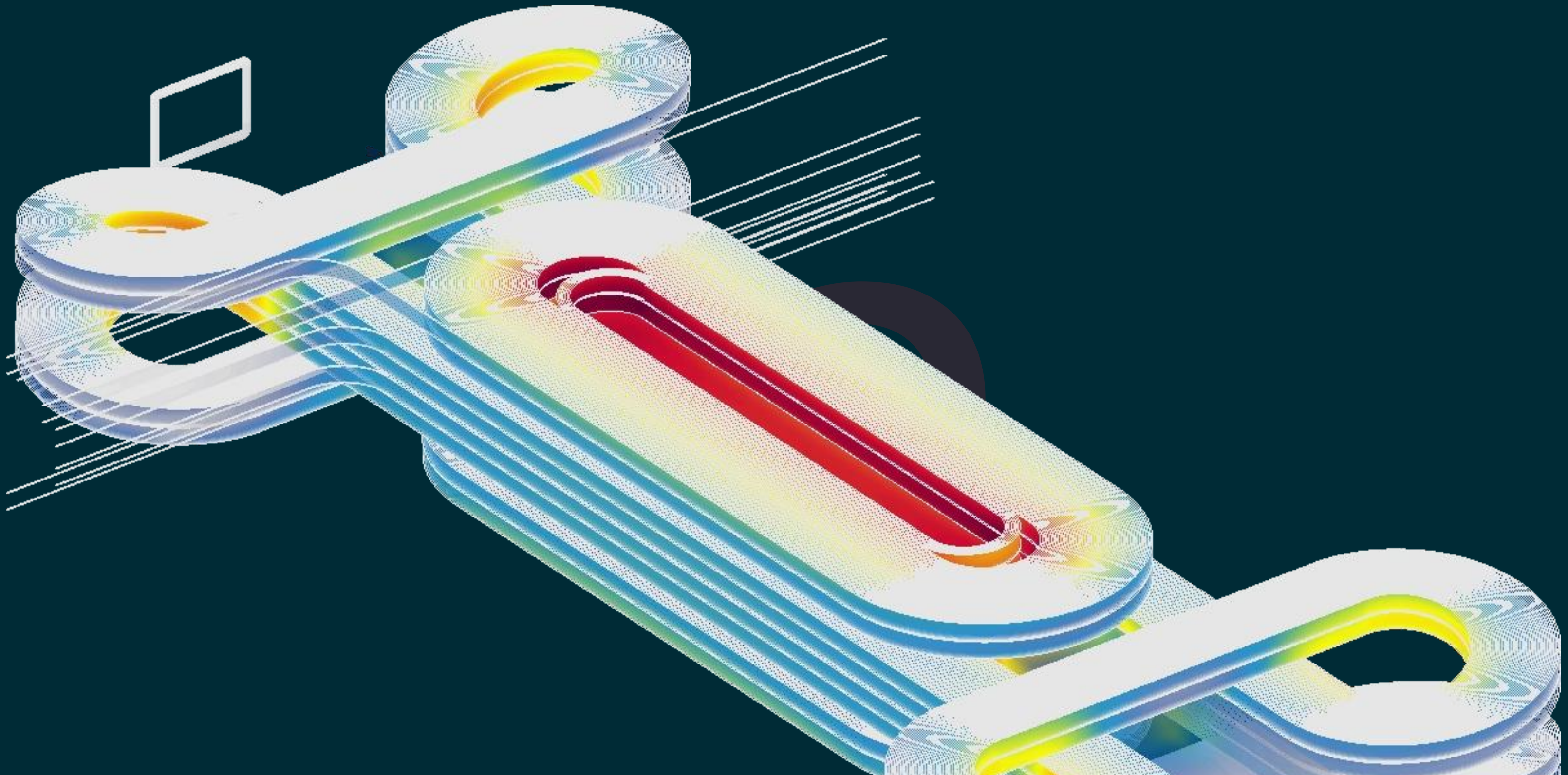
- With the test of this Feather-M2.1-2 magnet EuCARD2 came to an end April 2017
- However, CERN will continue building and testing Feather-M2.3-4 (with ultra high Jc Bruker cable)
  - Standalone Cold testing foreseen end of 2017
  - Background field tests foreseen start of 2018



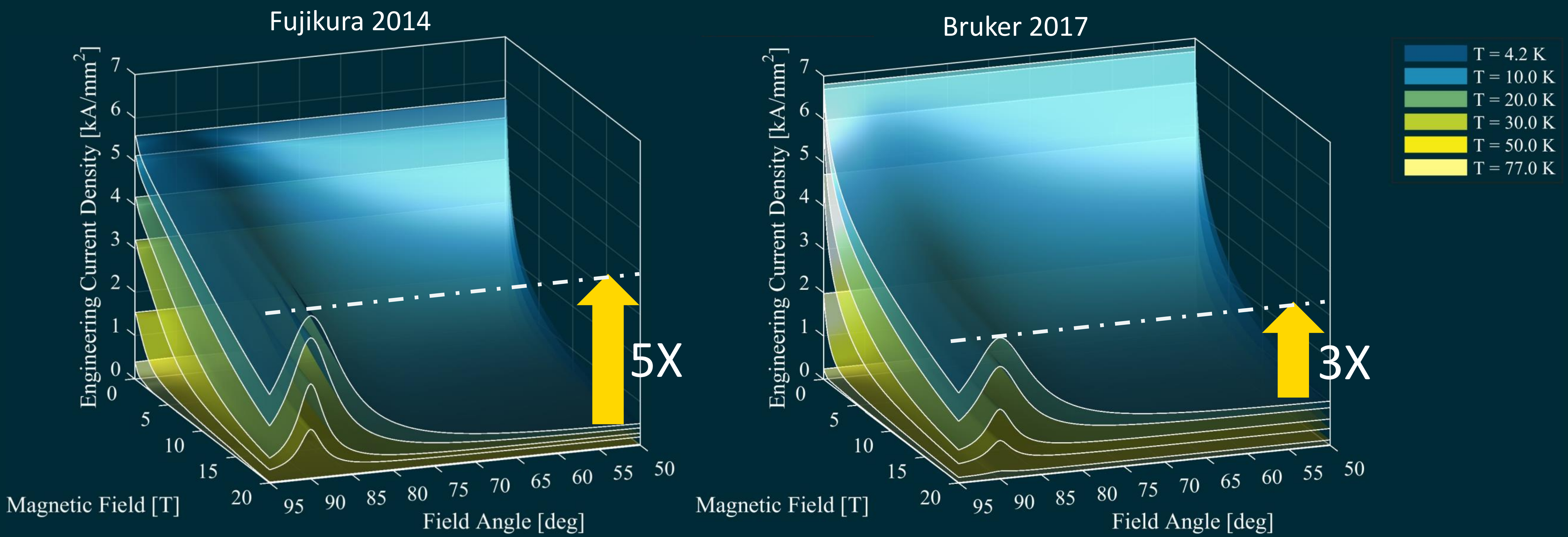
Cable for next Feather-M2.3-4
(this cable exists 2017)
1000A/mm² @(4.2 K, 20 T, pp)
= 14 kA

Lets TALK About the Future

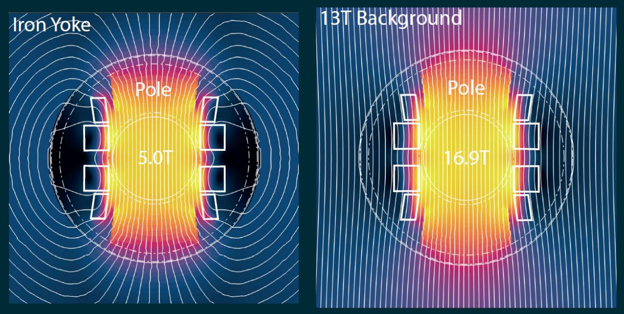
- The conductor development will continue within the ARIES collaboration
  - Aim consistent ReBCO coated conductor with Je > 1000 A/mm^2
- Long term CERN is initiating a 10 year development program to develop dipole magnets with magnetic fields beyond 20T
- Question: Based on what we have learned, what could a very high field magnet (20T+) potentially look like?
- Everything presented from here on in this talk is in early stages of development and is open for discussion …
  - In essence: these are just my initial thoughts. (=



(Re)Considering Conductor and Angular Dependence

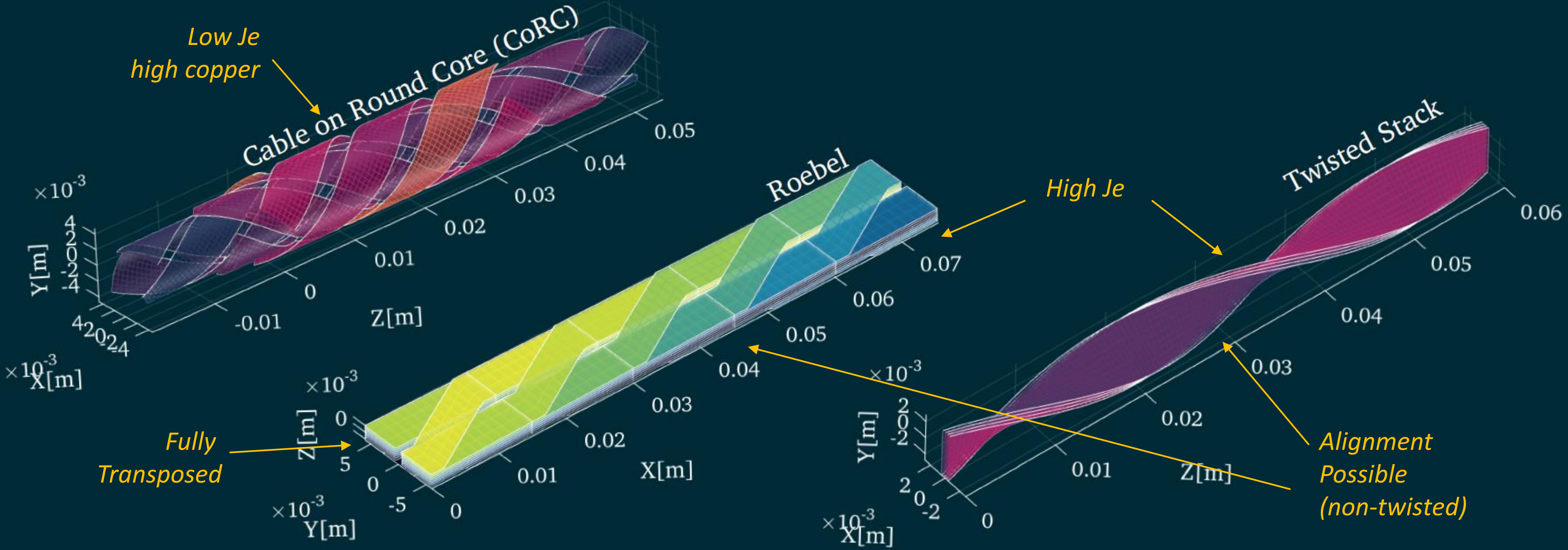


- Utilizing the anisotropy of the critical current was one of the main features of Feather-M2
- With artificial pinning angular dependence has become less
- Still seems useful to align the tapes though (also for magnetisation)



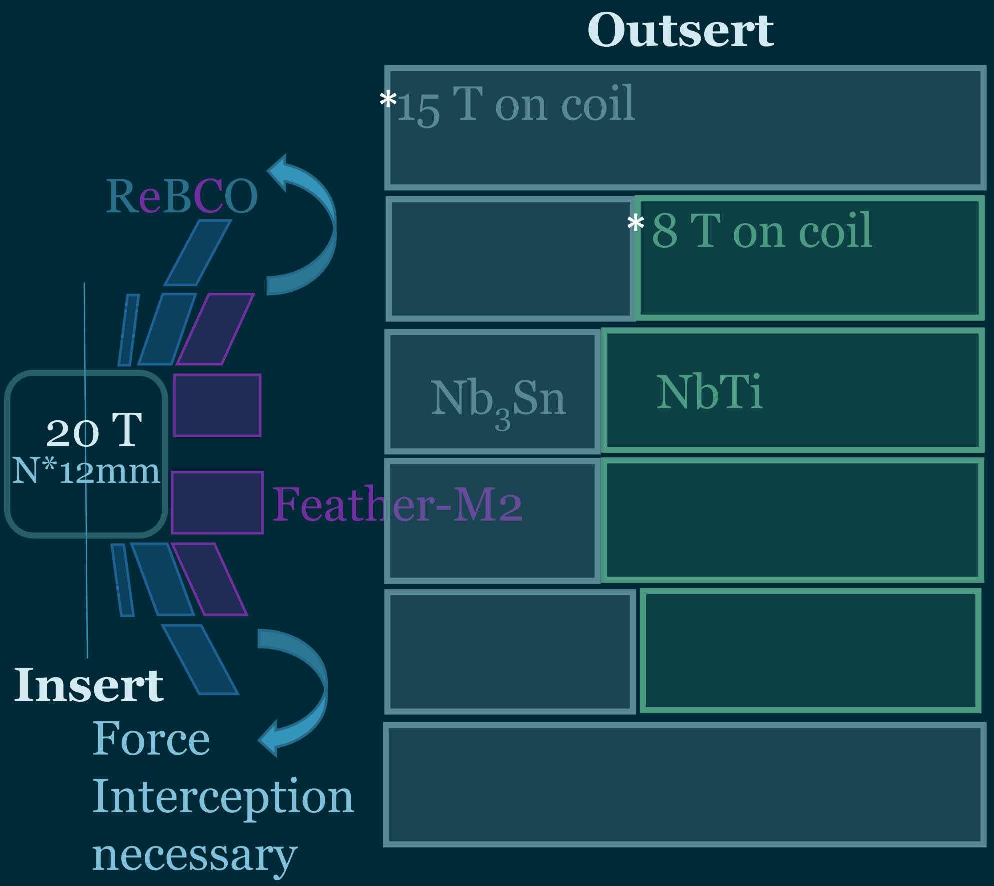
Cable (Re)Consideration?

- It is necessary to use a cable (or maybe non-insulated coils)
  - To allow the current to redistribute between tapes when quench/resistance does occur (like non-insulated coil)
  - To mitigate for possible defects inside the tapes (allows for production of longer lengths)
- Several options are available:

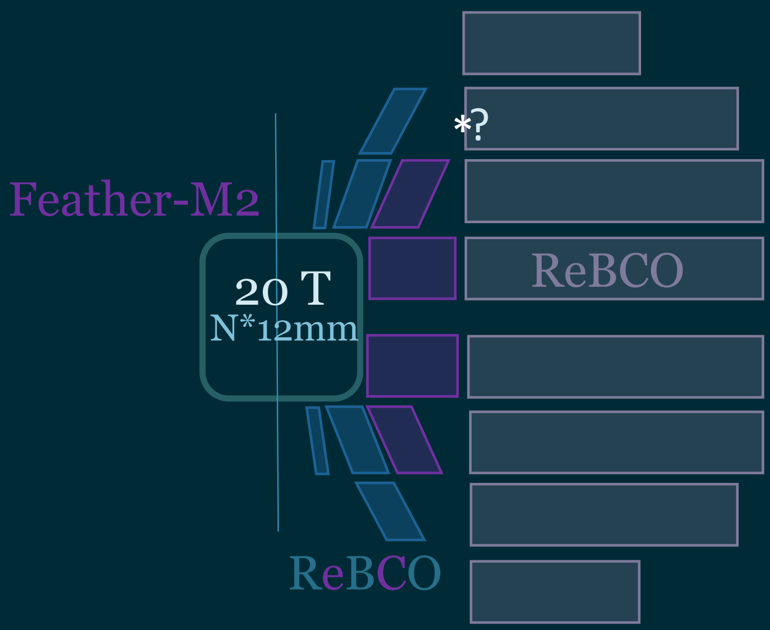


Layout (Re)Consideration

- Hybrid Magnet – ReBCO Aligned Block - Nb_3Sn (+NbTi) Block
  - Lower conductor cost, but need to perform heat treatment of Nb_3Sn
  - Can consider Cable in Conduit Cables (CiCC) for outsert
  - Need pre-compression of Nb_3Sn layers
  - Need to separate forces from insert and outsert for Nb_3SN has 150MPa pressure limit



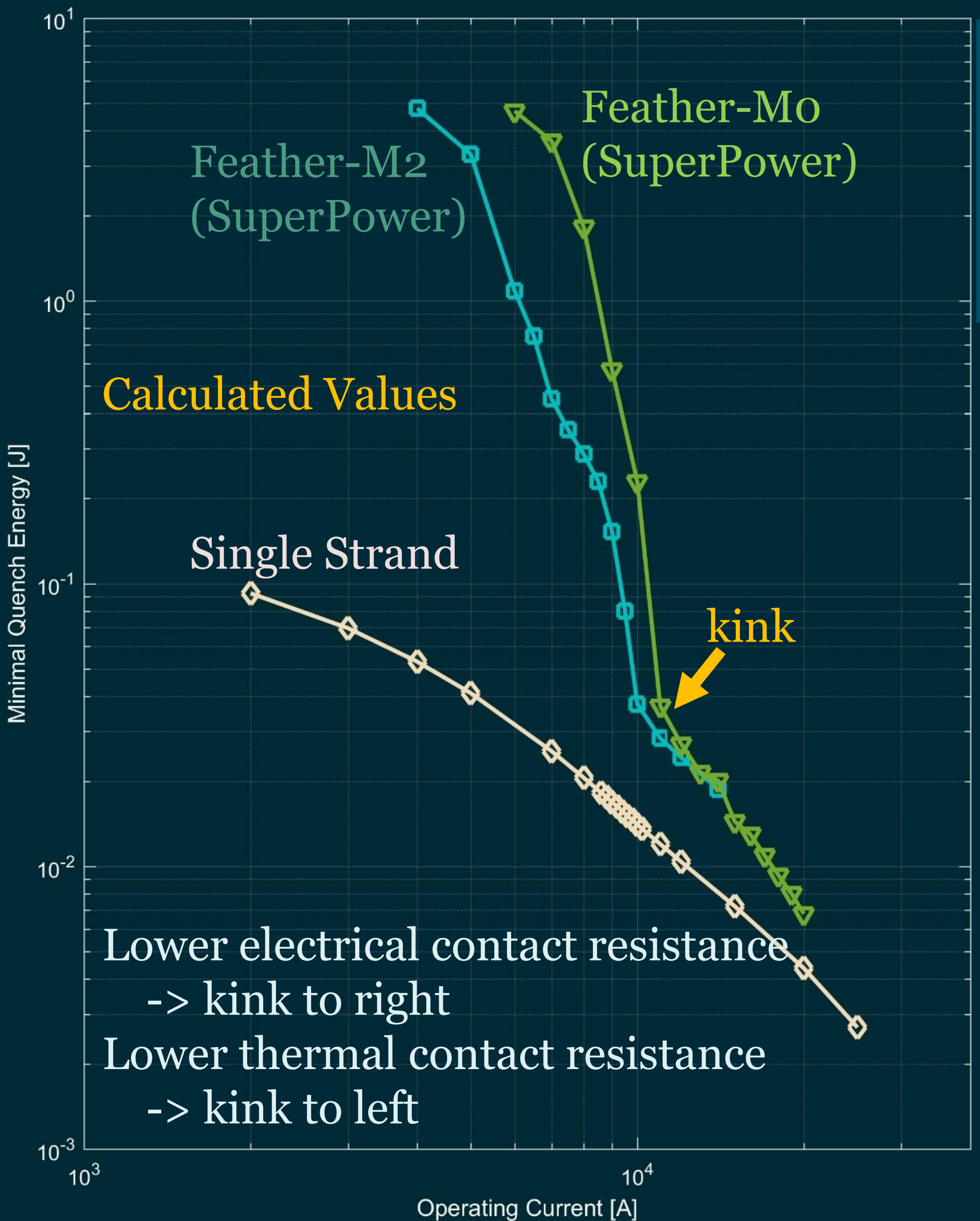
- Full HTS Magnet – ReBCO Aligned Block – ReBCO Block
  1. Operation in helium gas flow at variable temperature possible preferable especially for prototype (below 20K no energy margin)
  2. Pre-compression not necessary from stability point of view
     - Rectangular aperture possibility (cooling pipes in corner)
  3. pressure resistant up to 400MPa (utwente)
     - Stress interception not needed?
  4. Use modular design to test coil parts separately
  5. Higher overall current density possible – smaller coil
  6. Easier to approximate optimal coil shape
  7. NbTi grading possible?

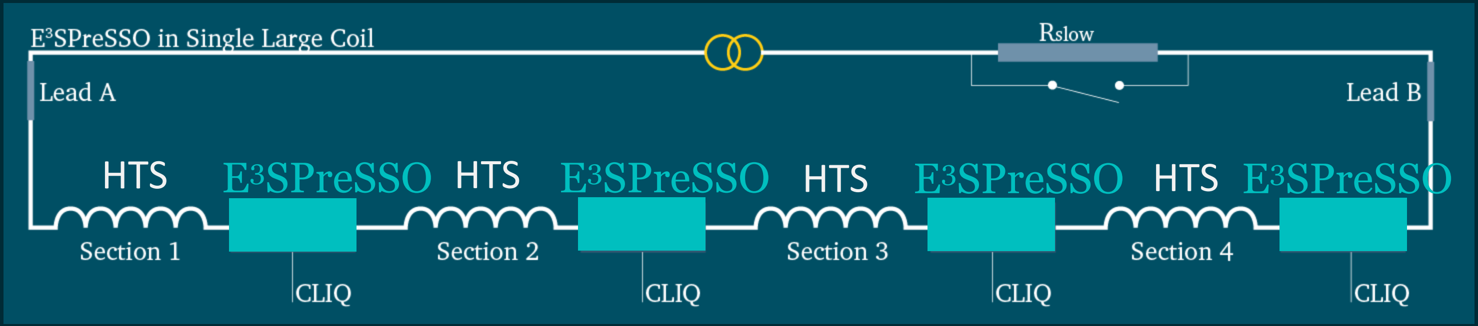


Glyn's Elephant

Lets go with This one for now (=

Quench Protection (Re)Consideration

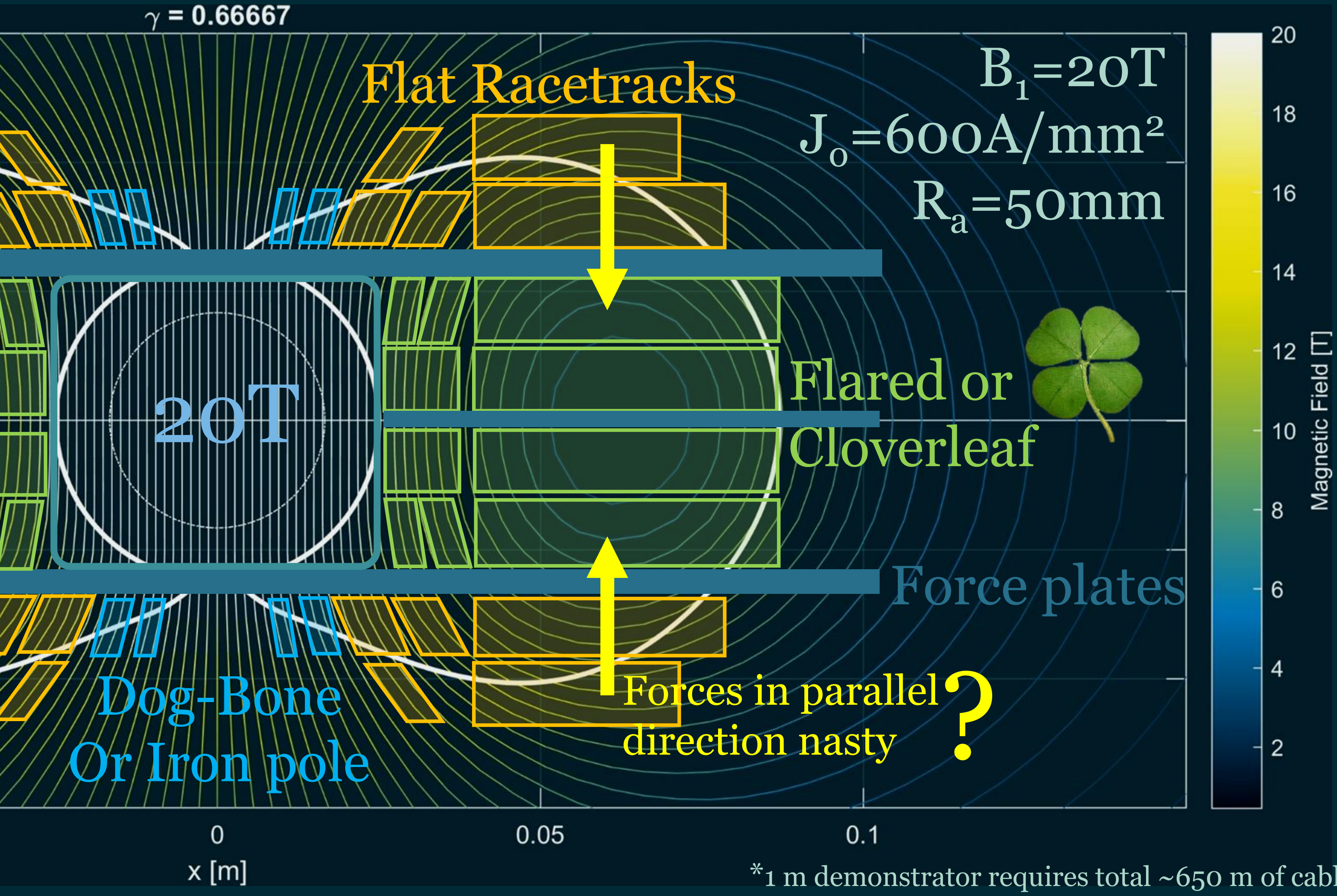




- With such high current densities and energies quench protection for accelerator sized magnets becomes a serious challenge …
  - High MQE and low Vnzp: CLIQ and Heaters can **NOT** work!
  - Relying purely on stability is very hard to sell
  - We have been following the E³SPreSSO idea for a while but turns out you need a lot of units (8 per meter) to extract energy in required 30 ms
  - Hopefully the result in Feather-M2.1-2 can be reproduced reliably so that the magnet can be protected by slow abort

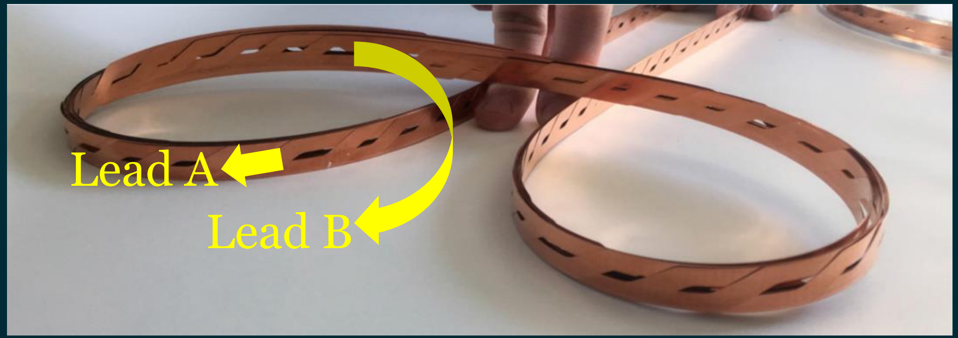
Initial sketch and possible coil end

- Conceptual sketch of a 20T magnet (using idealized coil shapes as base)
- However the coil-ends are not to be ignored, feasibility of magnetic field alignment in coil ends requires extensive study (to be done)

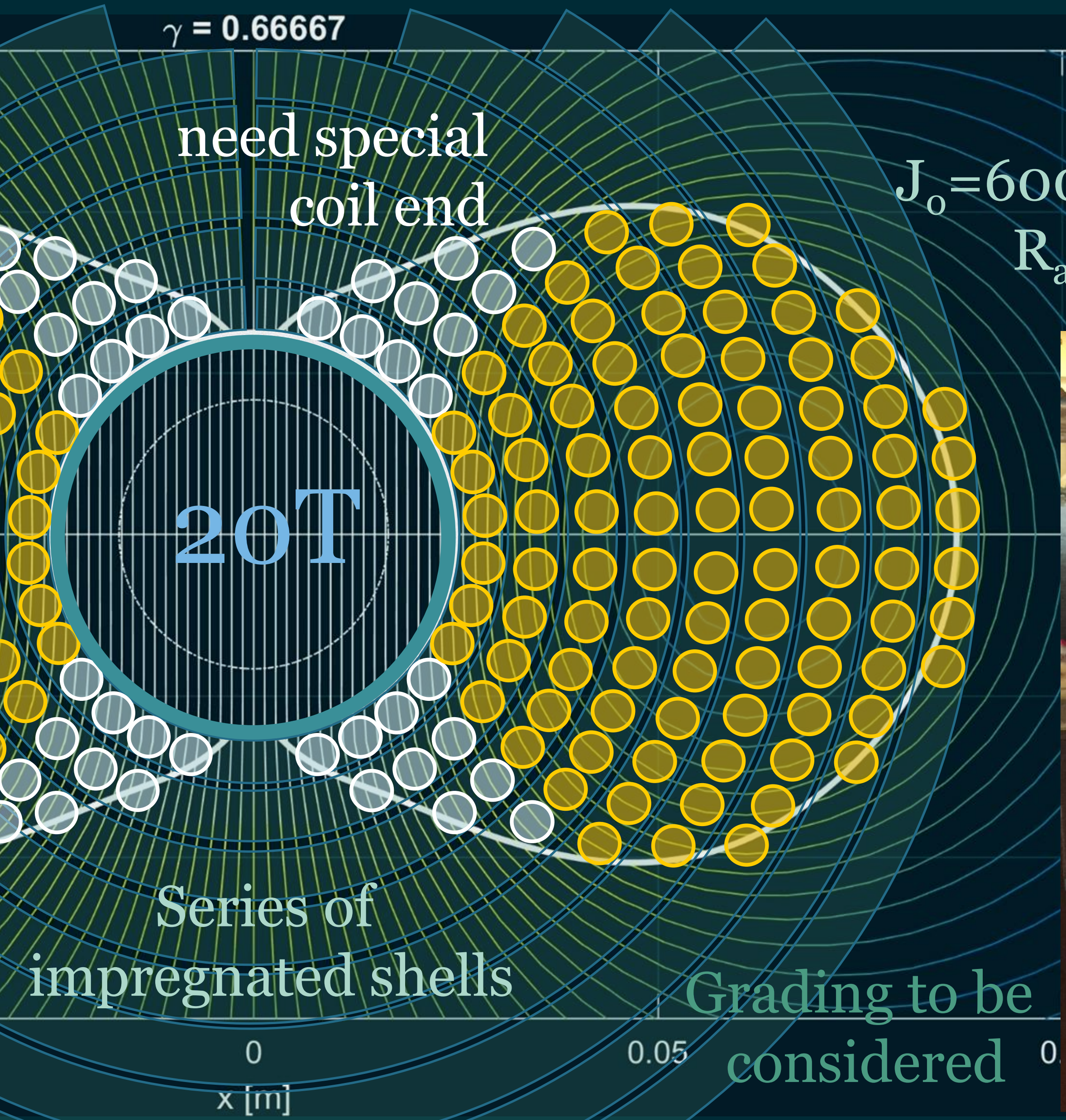


*1 m demonstrator requires total ~650 m of cable

- Clover leaf (RG) coil ends
  - No hard-way bending (non-twisted stack possible)
  - Allow to take lead out on both inside and outside of single pancake (E³SPreSSO)
  - Superconducting layer on outside of cable at ends (delamination?))=
  - Requires different winding approach (inside-out)
  - Dual-Aperture?

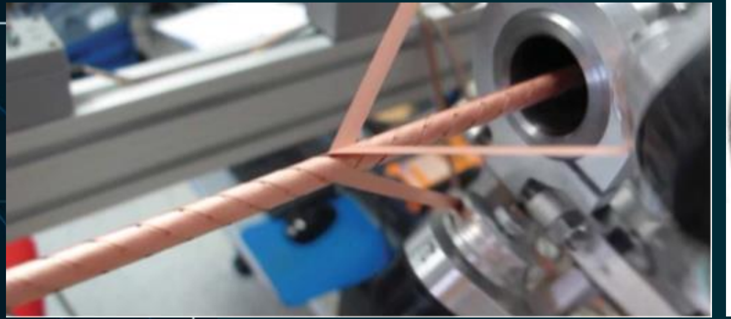


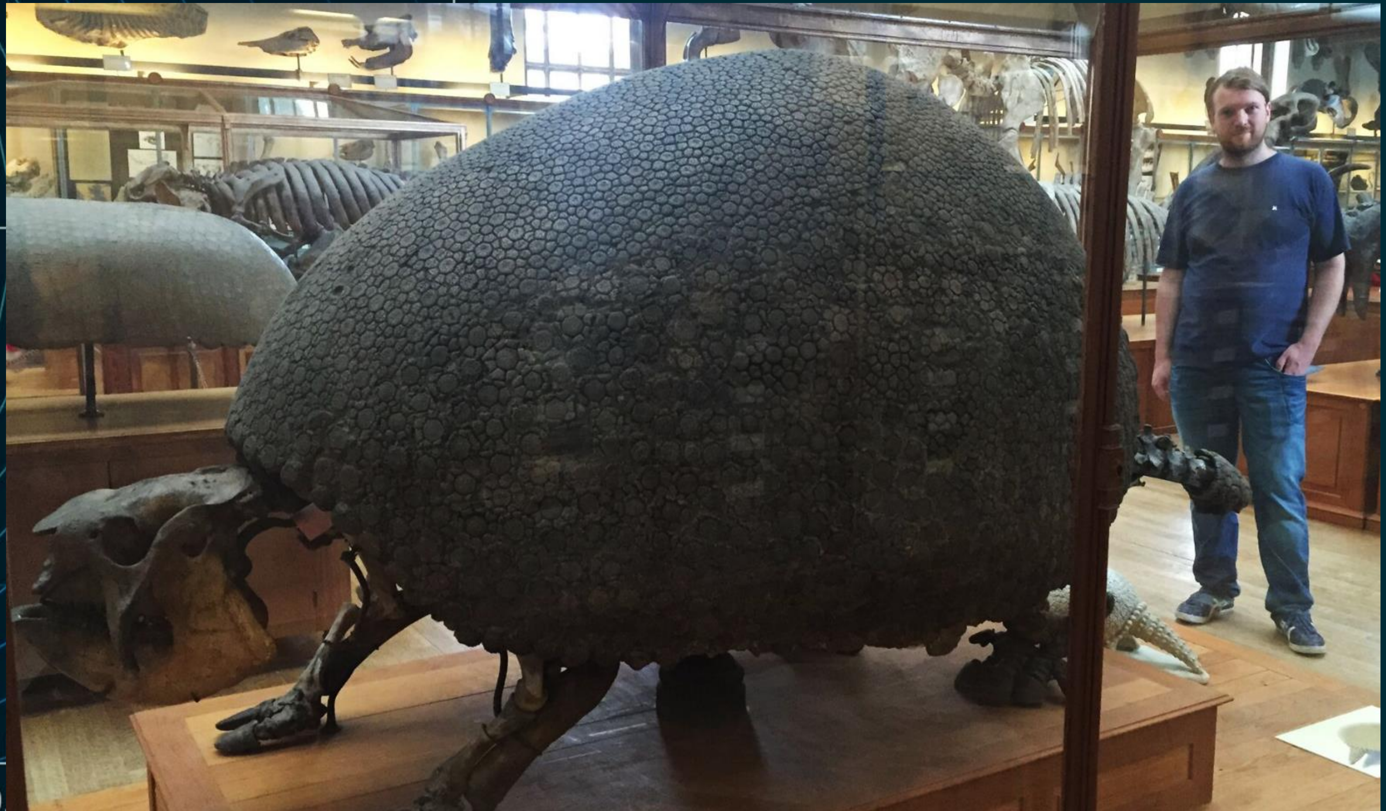
Armadillo coil layout sketch using CORC



B_1=20T
J_o=600A/mm²
R_a=50mm

Courtesy of advanced conductor technologies

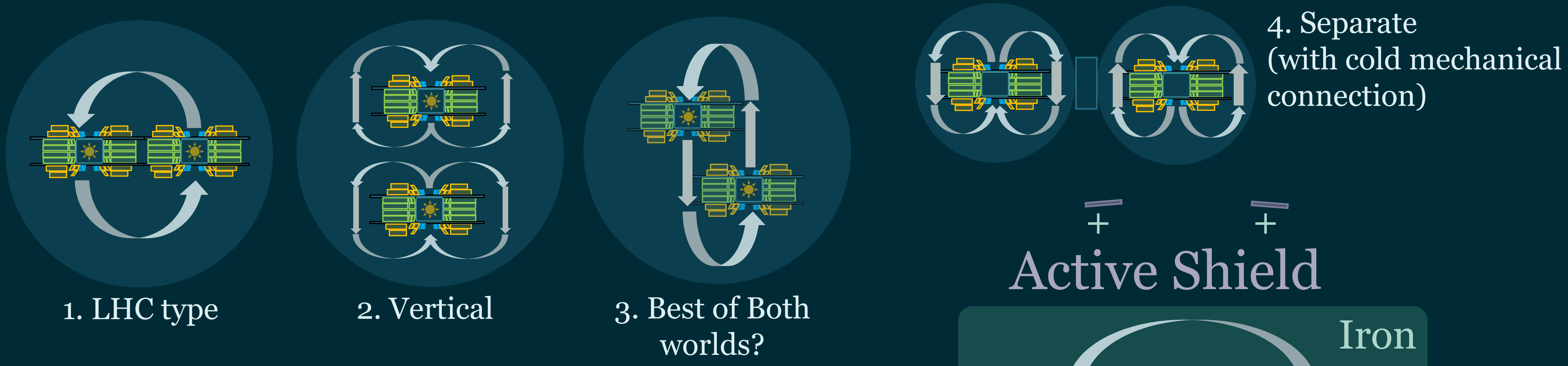




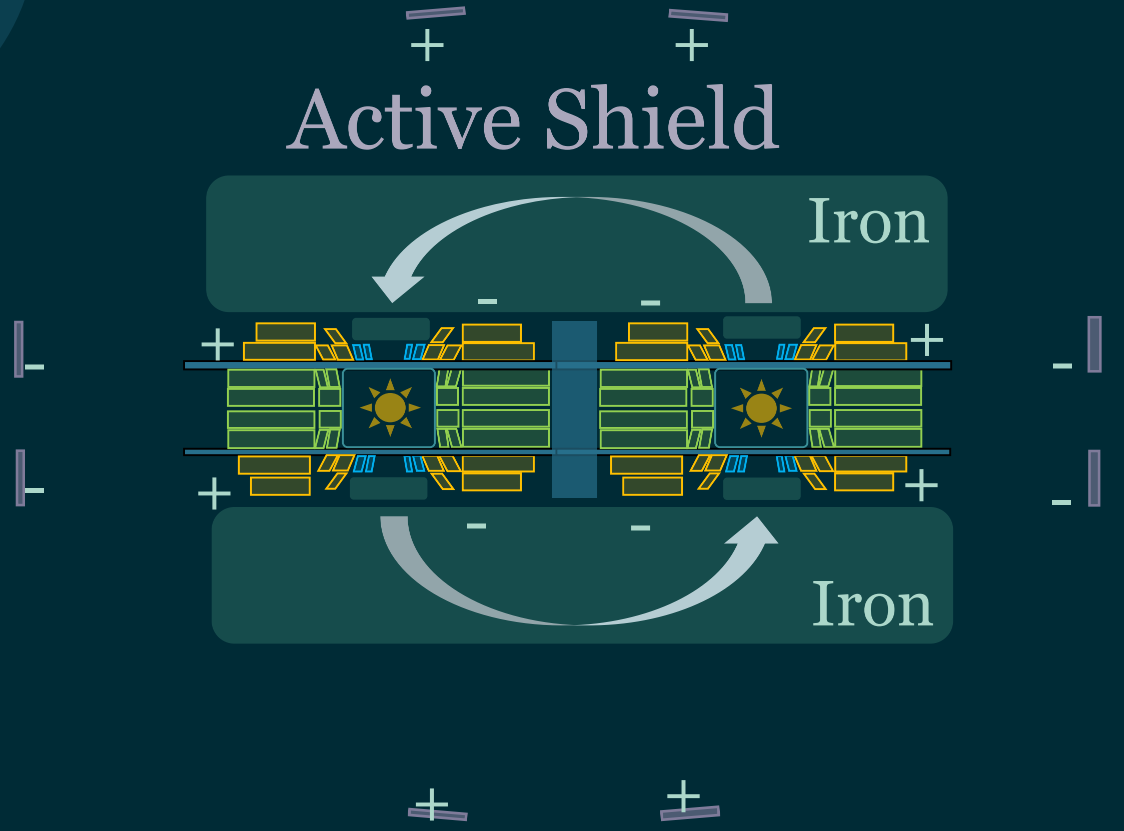
Museum of comparative anatomy, Paris, France

Thinking About Dual-Aperture, Yoke and Shielding

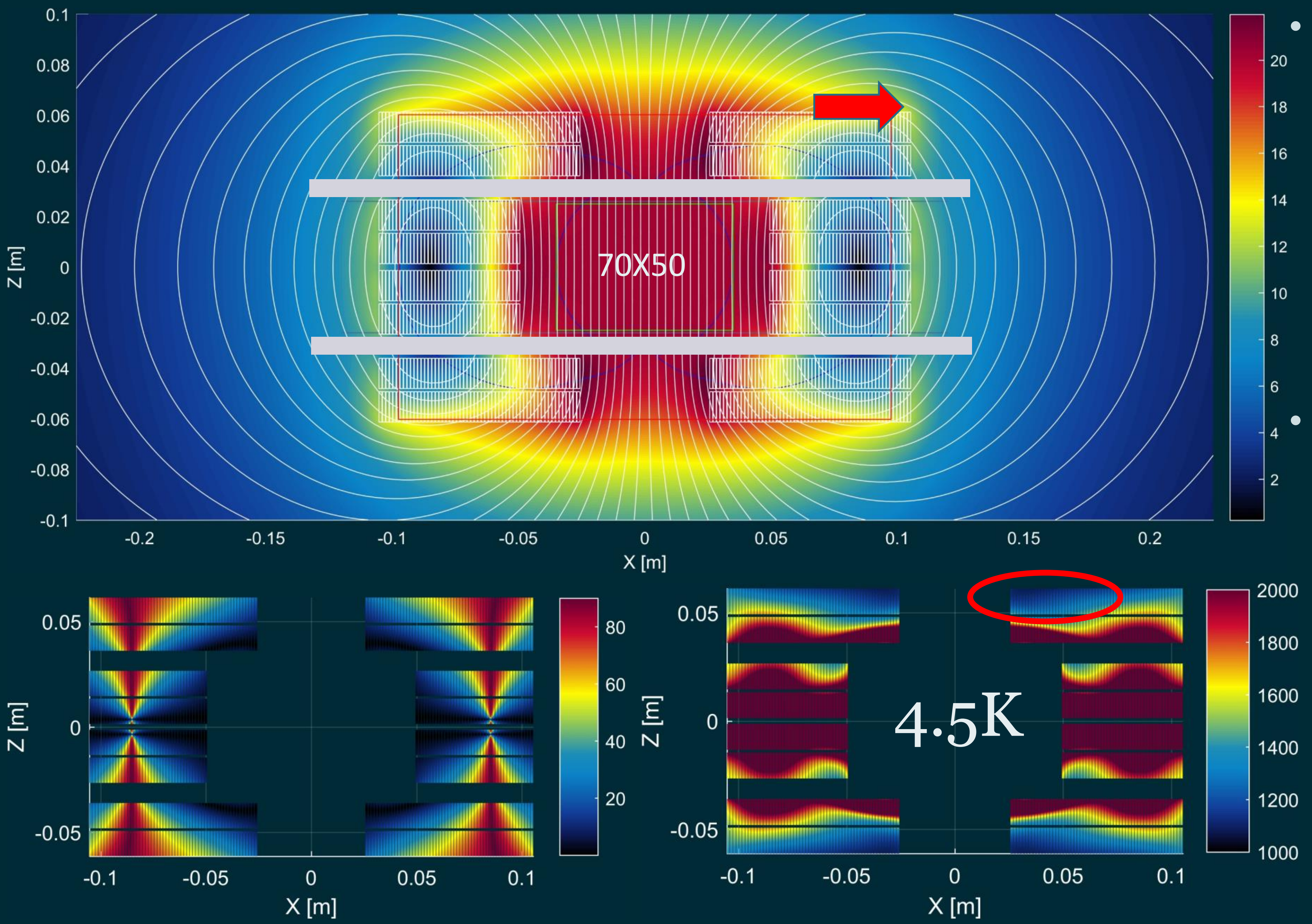
- Several dual-aperture configurations possible (to be studied)



- Cloverleaf coil ends only possible for 2, 3 and 4
- Relatively large quantity of iron needed to reduce stray field - may be impractical
- As an alternative the stray field can be reduced by active shield coils (quadrupole configuration)
  - Additional iron possible (free Tesla)
- Apertures must be mechanically separated
- Thinking about implementing 3D parallel MLFMM-GFUN or MLFMM-BEM-FEM codes …

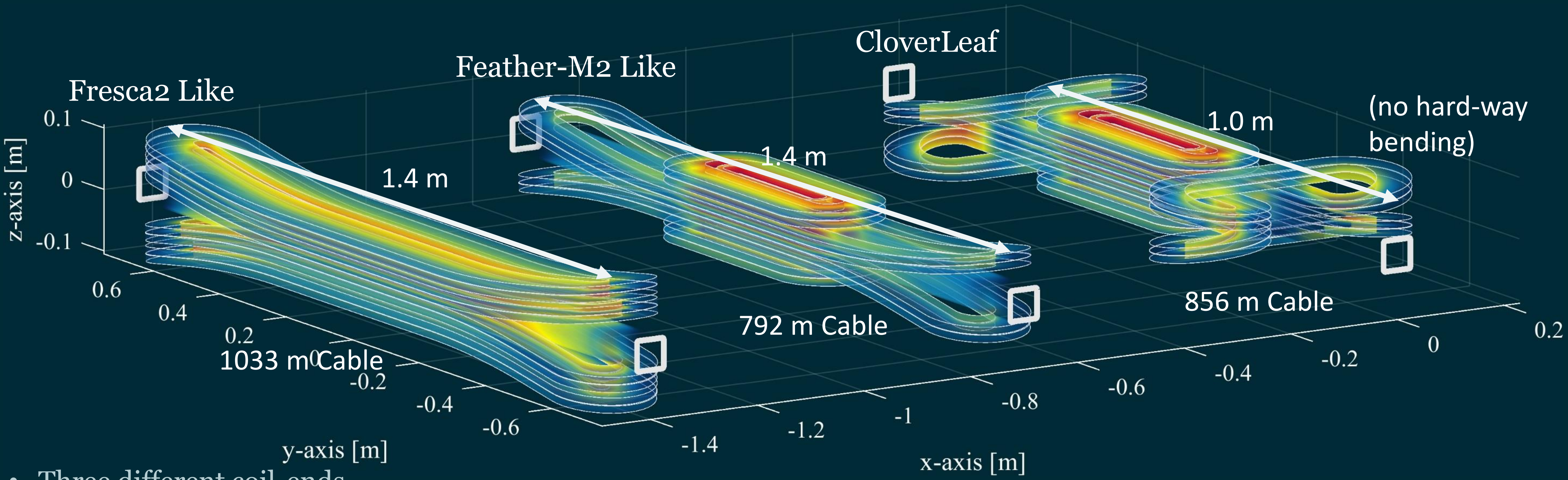


First cross-sectional layout



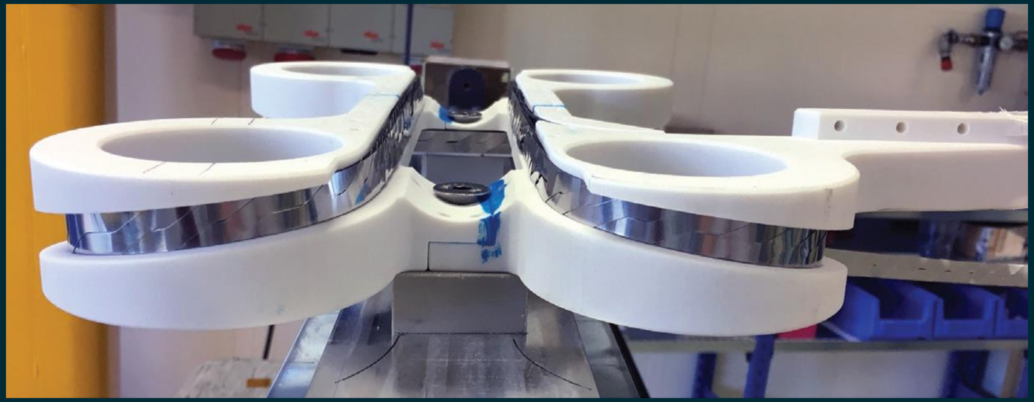
- Coil Properties:
  - Central Field 20 T
  - Current density 700 A/mm²
  - Aperture 70 X 50 mm
  - Sextupole 0.00 units
  - DecaPole 0.00 units
  - TetraDecapole 0.83 units
  - OctuDecapole -0.02 units
  - Coil area 130 cm²
- Lowest thermal margin on outermost deck
  - This issue is difficult to fix with conductor alignment
  - Perhaps grading between the aligned part and non-aligned part
  - In most crude approximation using different cables between upper and central deck (to be implemented)
  - Back to Insert (2 decks)-Outsert (4 decks)?

Comparing Coil-Ends

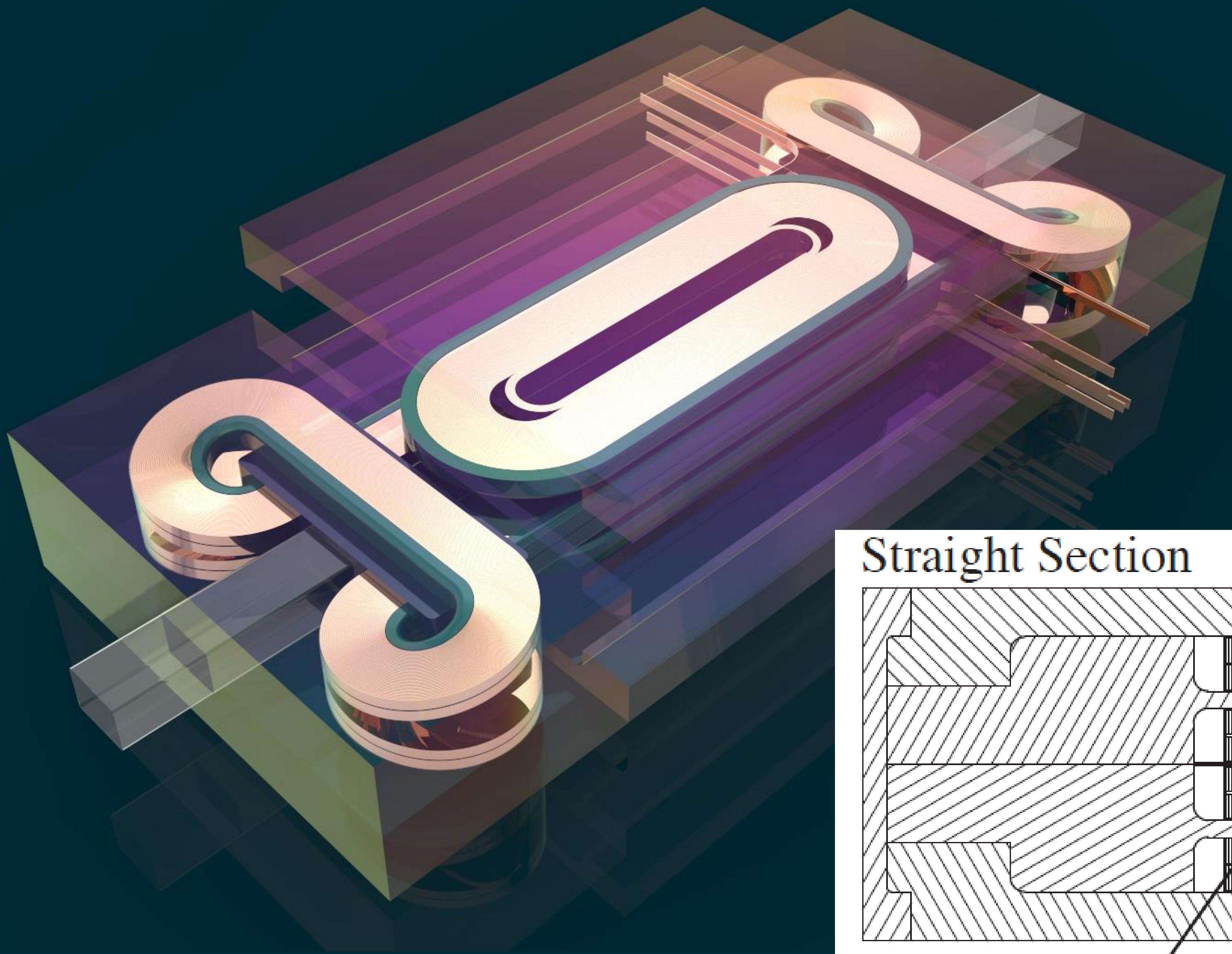


- Three different coil-ends
  - Fresca-2 like : less end-effects in harmonics
  - Feather-M2 like : minimal conductor in ends
  - CloverLeaf : no hard-way bending (allows for winding stack, Roebel (baseline) and non-insulated coil), significantly shorter ends

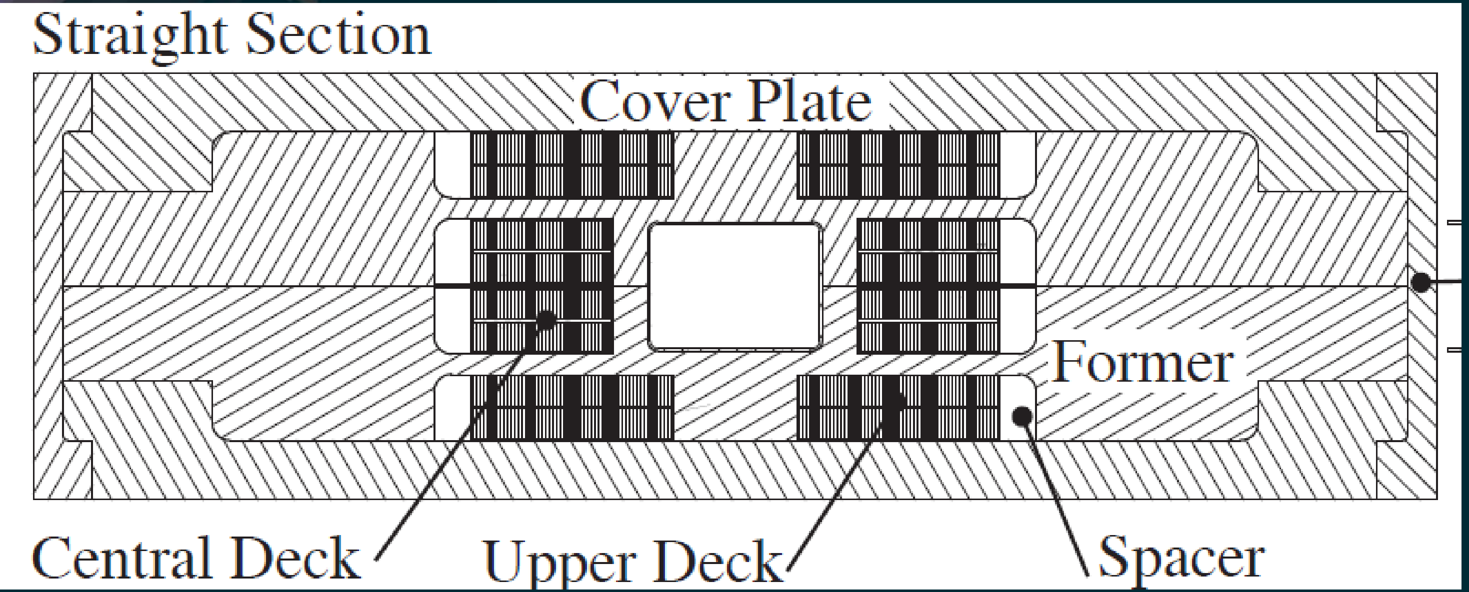
- Winding of the cloverleaf requires new approach: wind outside-in on the straight section
- We have performed a dummy cable winding test of a five turn CloverLeaf to find potential issues

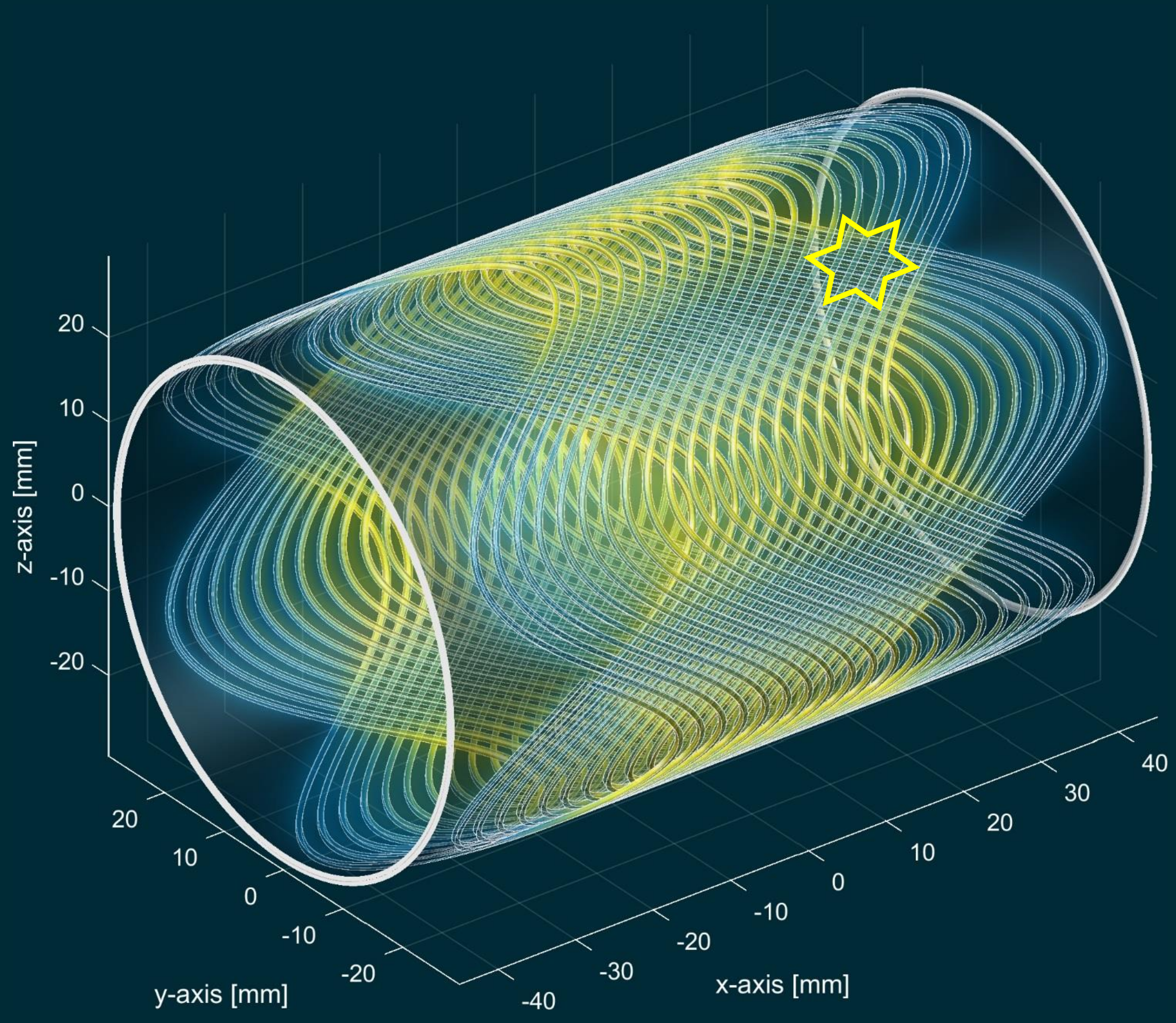


Mechanical Structure



- The coils are all impregnated separately after which they are mounted onto a former
- The former provides a wall for intercepting the transverse and longitudinal forces





One more technology that may prove to be necessary

Persistent Current Shim Coils for Accelerator Magnets

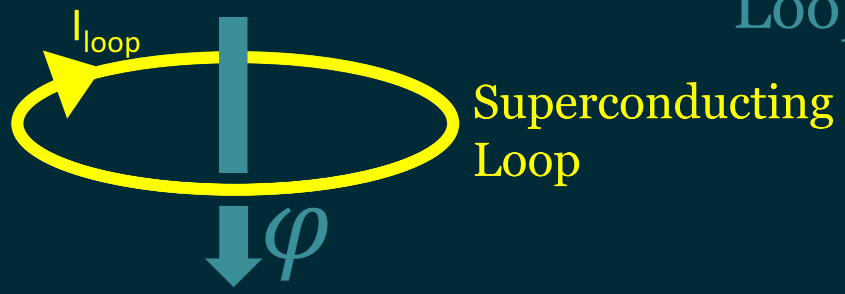
-The Magic Magnet-

[1] J. van Nugteren et. Al. "Persistent Current Shim Coils for Accelerator Magnets", *Technical Report, CERN, 2016*
[2] J. van Nugteren, "High Temperature Superconductor Accelerator Magnets", PhD Thesis, University of Twente, 2016
[3] A. Dael et. Al., "Auto Correction des Harmonicques du champ Magnetique d'un multipole pulse par enroulements supraconducteurs," Particle Accelerators, vol. 4, pp. 145–150, 1973, in French.

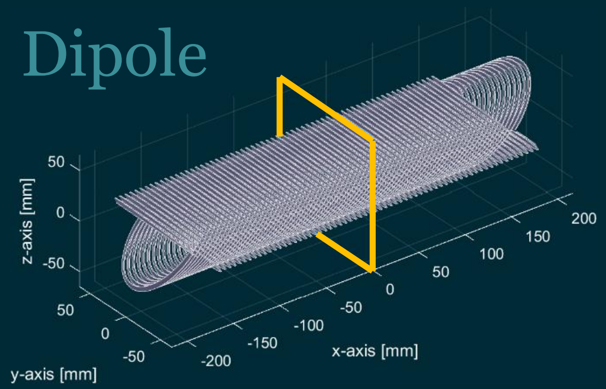
How does the shim coil work?

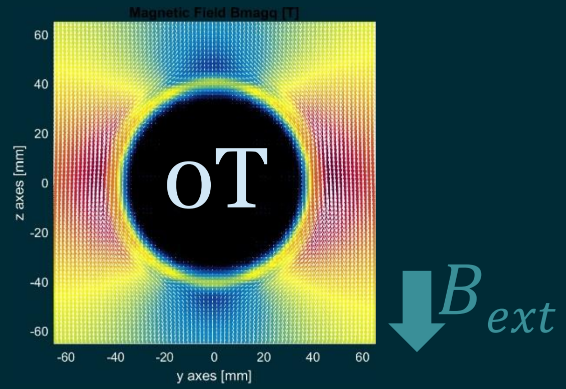
- Consider a superconducting loop
  - The persistent current I_{loop} induced in the loop keeps the flux φ inside constant at all times (up to its critical current limit)

Loop



Dipole

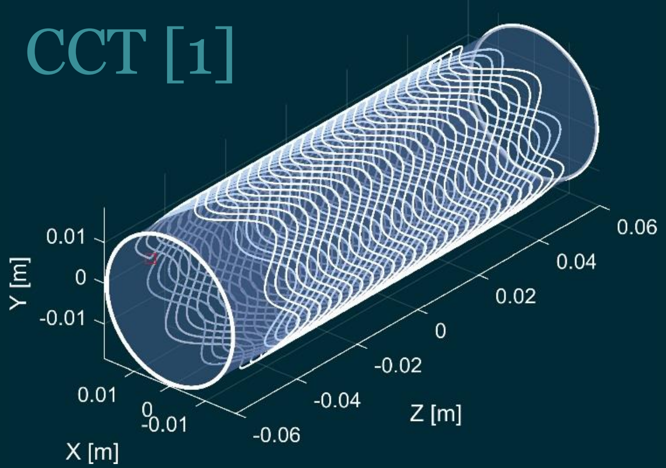




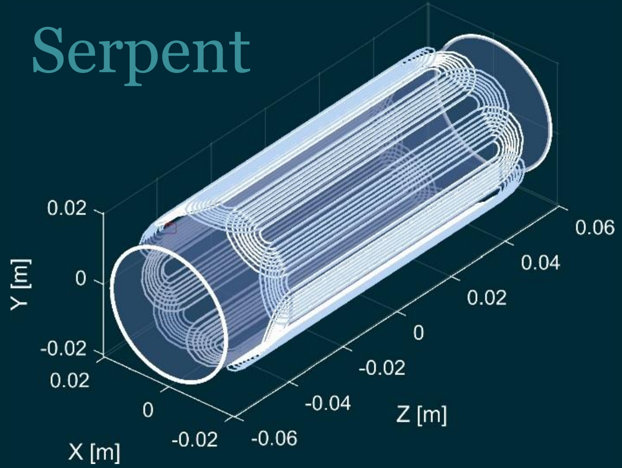
- In a persistently connected perfect dipole magnet the flux is specifically "linked" to the dipole component
  - When the outside field changes the dipole field in the aperture is kept constant (at zero)

- In similar fashion it can also be applied to higher order coil harmonics
  - A persistent pure Sextupole coil entirely filters out the Sextupole component
  - But is completely insensitive to other harmonics
  - Multiple shim coils can be nested to filter out several components
  - Shim coils can be of CCT or Serpent types

CCT [1]



Serpent



[1] D. Meyer and R. Flasck, "A new configuration for a dipole magnet for use in high energy physics applications," Nuclear Instruments and Methods, no. 80, pp. 339–341, 1970.

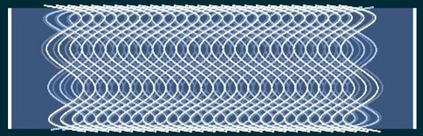
Shim Coil Numerical Analysis

- Shim corrects its integrated harmonic exactly over its magnetic length, local errors remain.
- Here is demonstrated on static field, but concept also works for dynamic

very crappy dipole (=

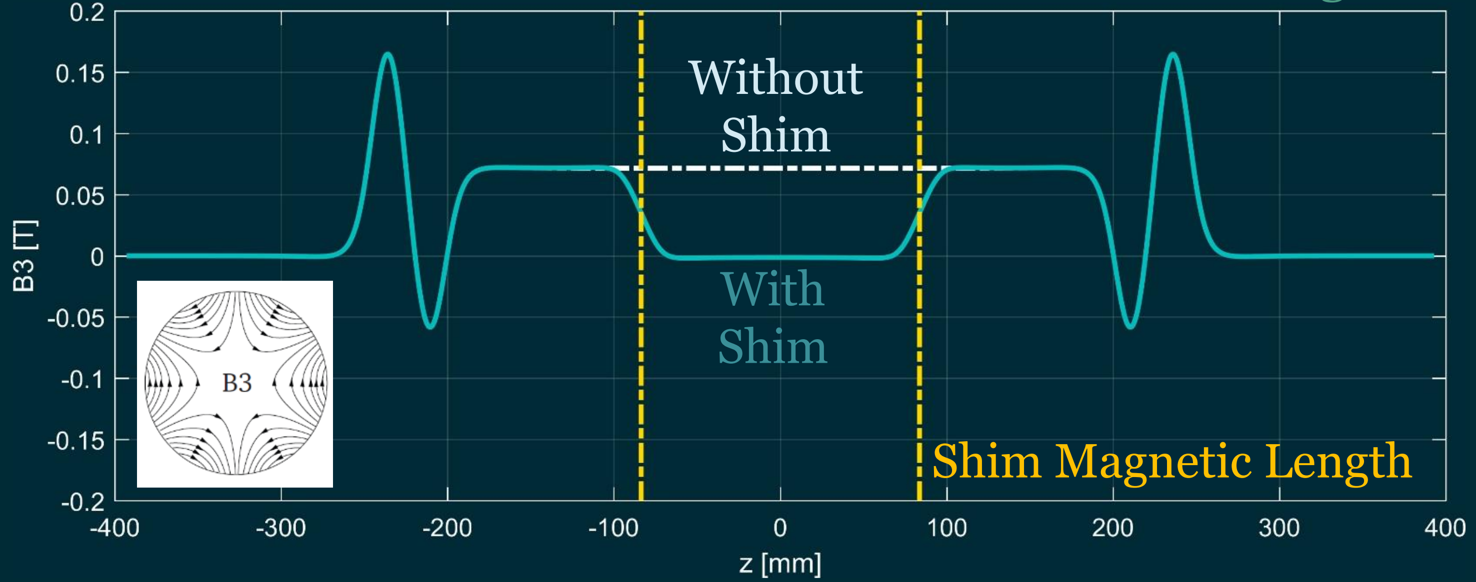
+

sextupole (B_3) shim coil

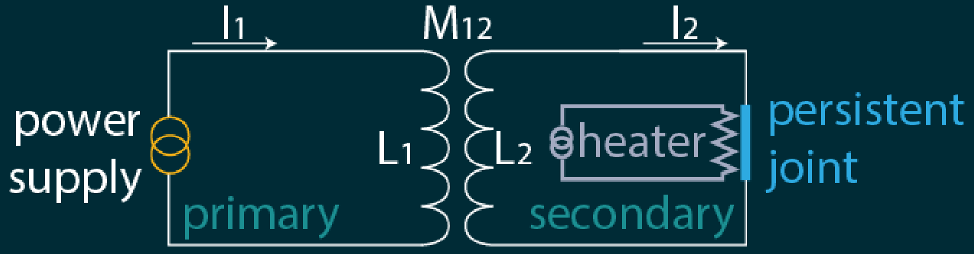


sextupole at 2/3 aperture along axis

=

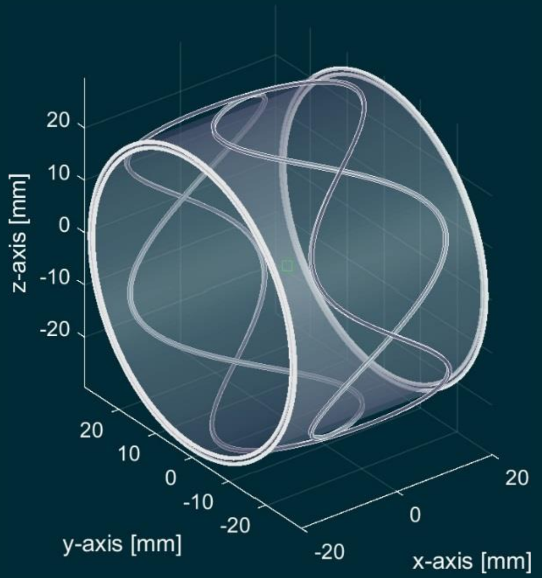


- The current in the shim can be calculated using the mutual inductance matrix of the system (as a transformer)



$$\frac{I_2}{dt} = \frac{M_{12}}{L_2}\frac{I_1}{dt}$$

- Where M_{12} and L_2 are calculated using my *Field 2017* code

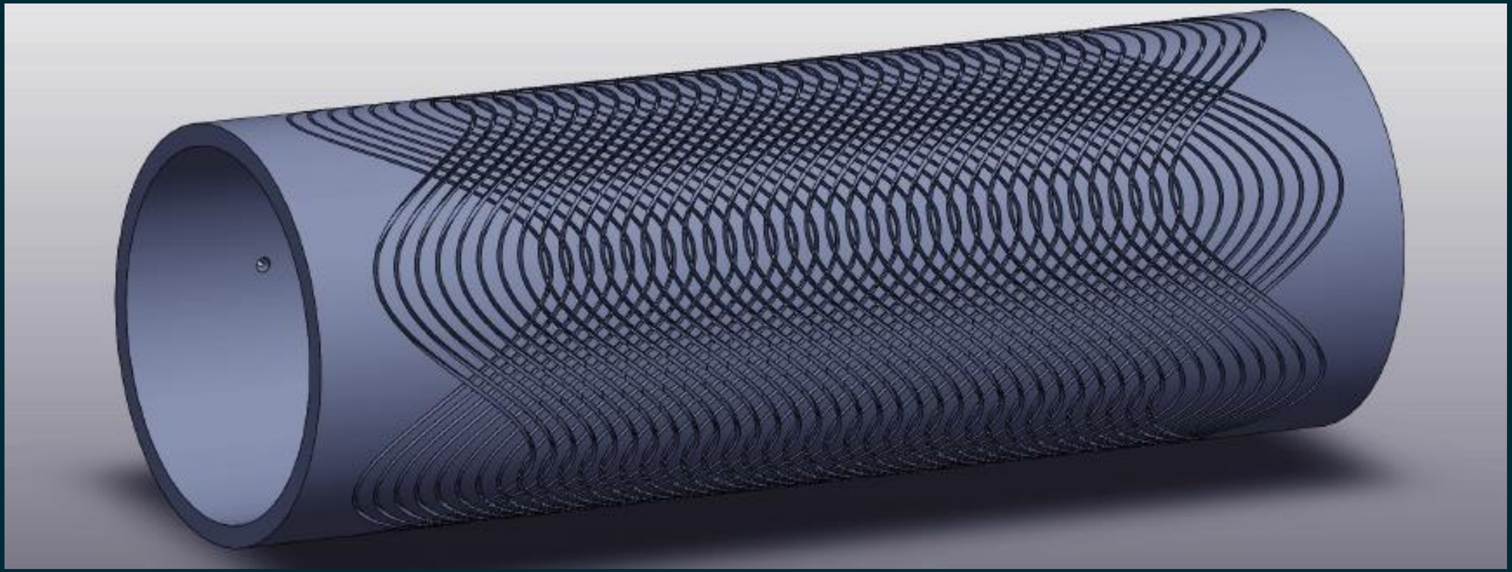


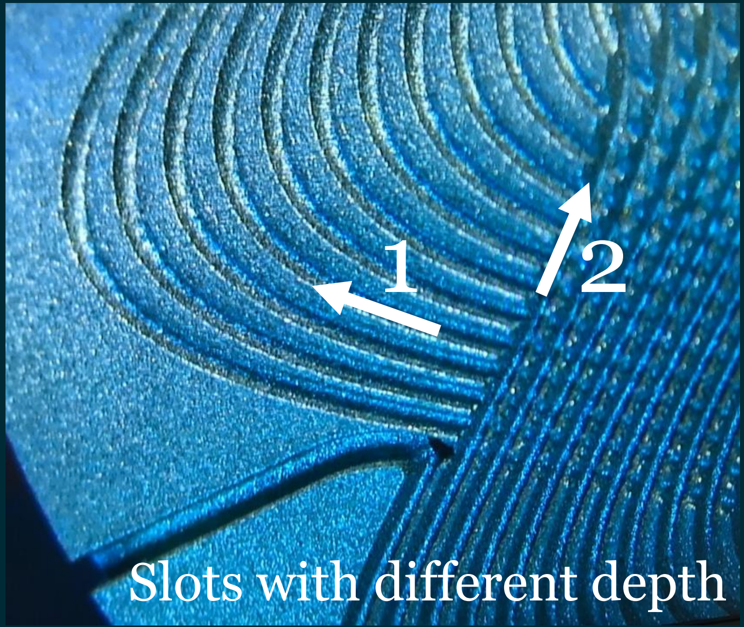
- A repeated pattern of single lanes also works due to mutual coupling
- Layers are not electrically connected
- Vapour deposition ReBCO on tube?

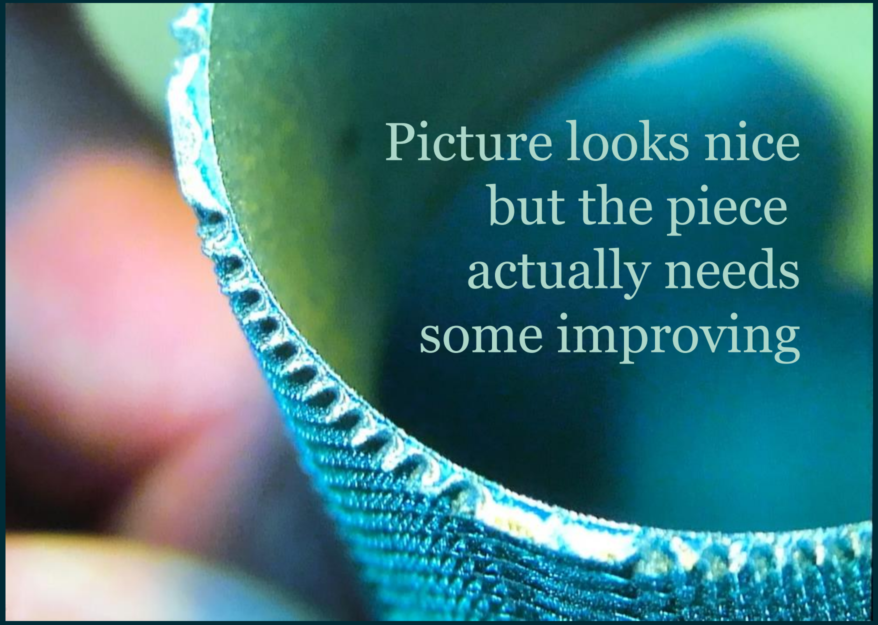
Construction of Demonstrator

- First sextupole demonstrator is under construction at CERN using NbTi (low field) wire in channel
- Persistent joint technology developed at Oxford University [1] (thanks Greg)
- Using persistent mode copper nickel switch from Oxford Instruments
- Test in 11T or Feather-M2 magnet

[1] G. Brittles, "Persistent joints between NbTi Superconducting wires", PhD Thesis, Oxford University, 2016







Talk Summary

- First Feather-M2.1-2 (SuperOx, Sunam) magnet was tested successfully and EuCARD2 has ended
- CERN is initiating 10 year HTS program
  - By building another Feather-M2 with high performance cable
  - By developing a 20T+ demonstrator accelerator magnet
- First mechanical ideas are present
- Need new method for dealing with quenches. Possibly early detection
- Persistent current shim coil can provide solution for field quality
- Cost must come down to allow more people working with this remarkable material (need commercial application for ReBCO)
- Looking forward to start building (=

Thank You

for your attention

Extra Slides

Why? – 2. High Thermal Stability I

Stability of HTS Conductor illustrated

Quenching LTS wire 100 µJ

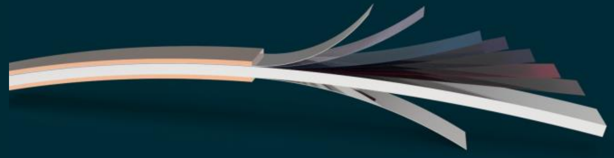
pin

10cm

Quenching an HTS Tape 100mJ

apple

10cm

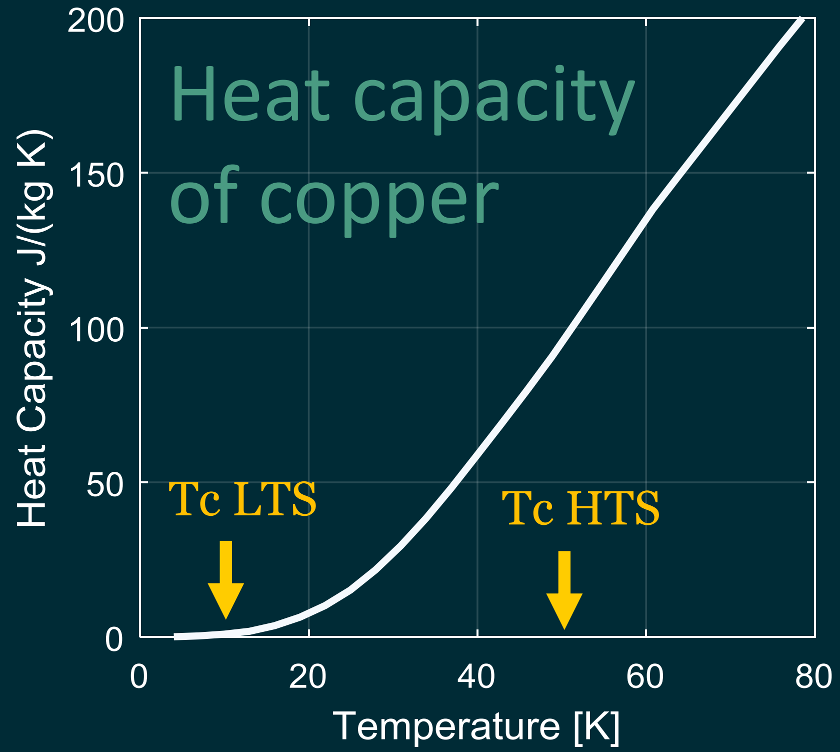


Quenching an HTS cable 1J+ (depends on geometry)

cannon ball

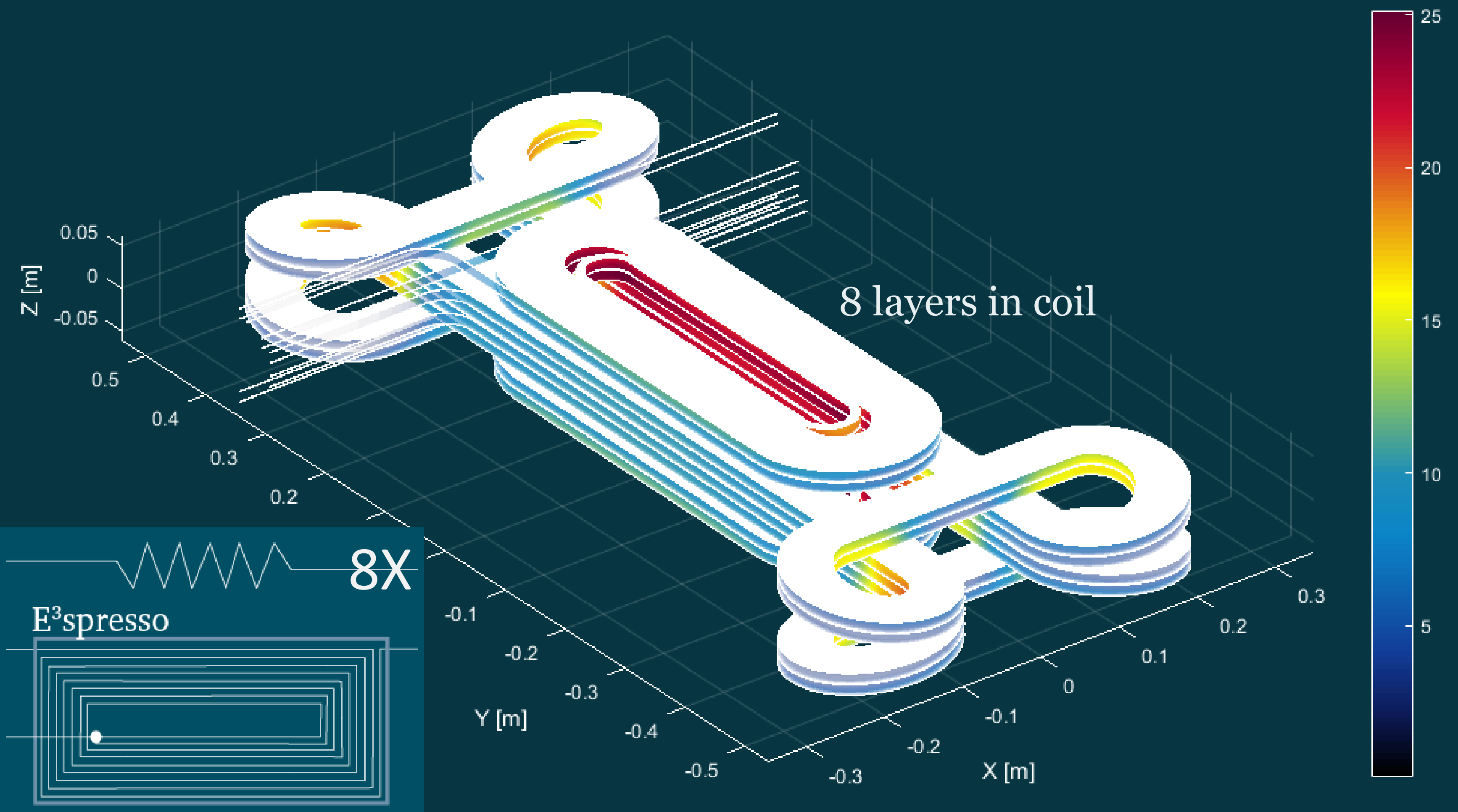
10cm

Due to high temperature margin it is super stable and does not quench randomly and thus it does not train



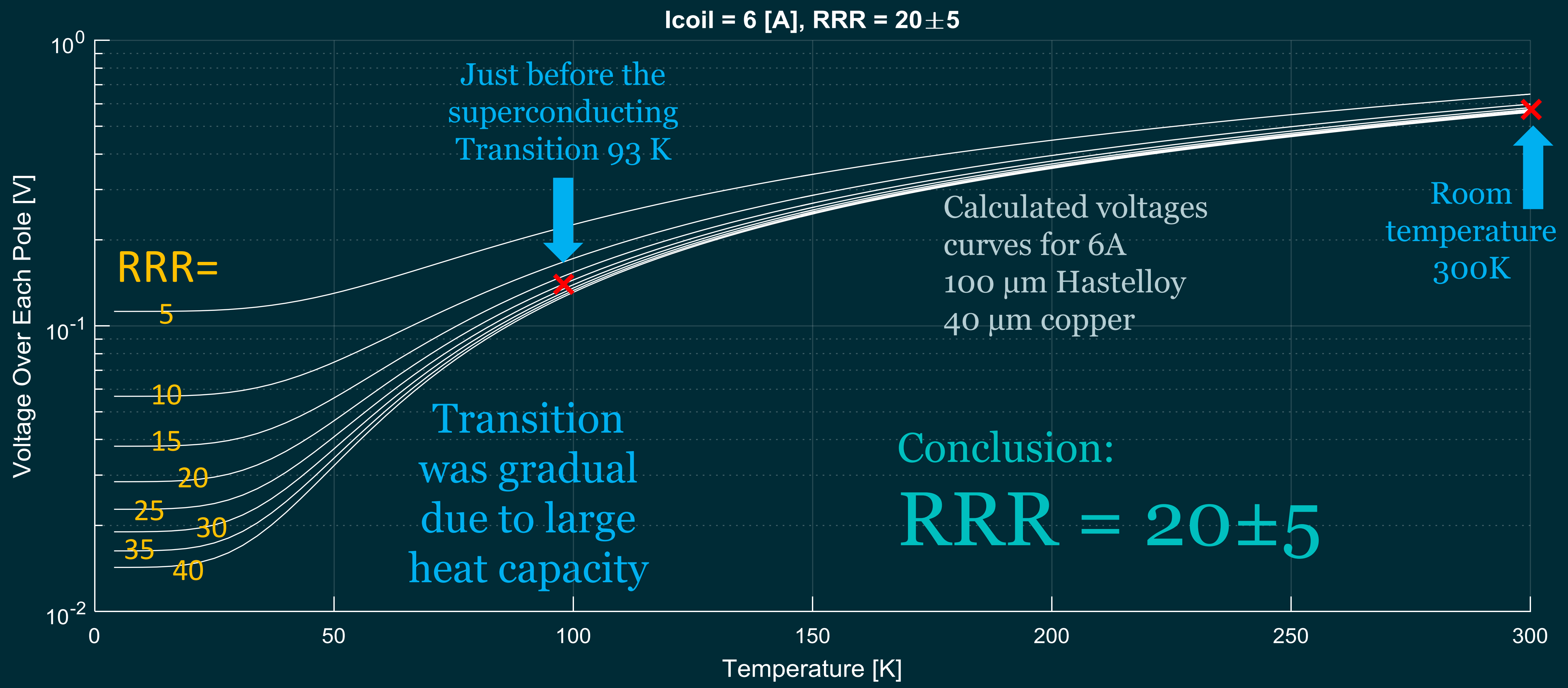
20T Prototype Magnet HTS Switch (evolution)

- Assuming our preliminary HTS 20T+ prototype design 900A/mm²
- Assuming 8 E3SPReSSO units with non-stabilized HTS switch stainless steel parallel resistor



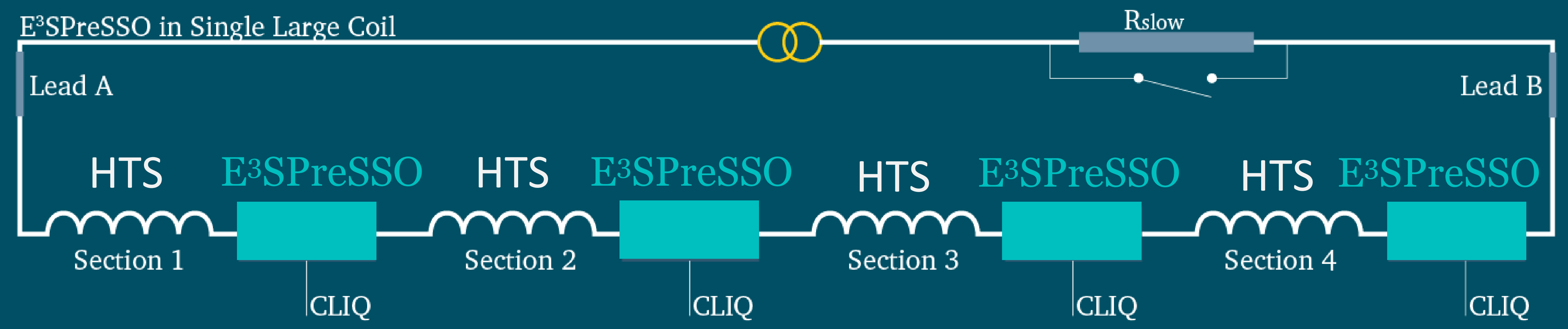
- The magnet:
  - Bop = 20 T,
  - Iop = 12000 A
  - L = 0.042 H (3 MJ)
  - Top = 20 K
  - 66% hastelloy, 1.3% silver, 26% copper, 0.7% YBCO
- E3SPreSSO:
  - N = 8, Vmax = 1000 V
  - Tmax = 250 K
  - T* = 135 K
  - 90% hastelloy, 1.8% silver, 0.9% YBCO
  - As = 15 mm²
- Result:
  - $l_s = 16.7\ m$
  - $A_p = 55.5\ mm^2$
  - $l_p = 11\ m$

Cooldown Critical Temperature and Triple-R



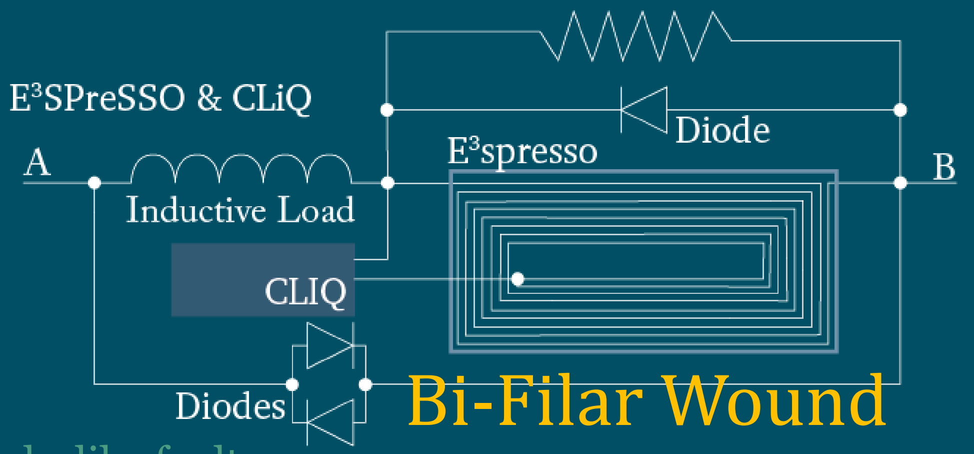
- Triple-R is defined between 10 and 273K
- Voltage only measured at 95 and 300K for a current of 6A

How E3SPreSSO Works I



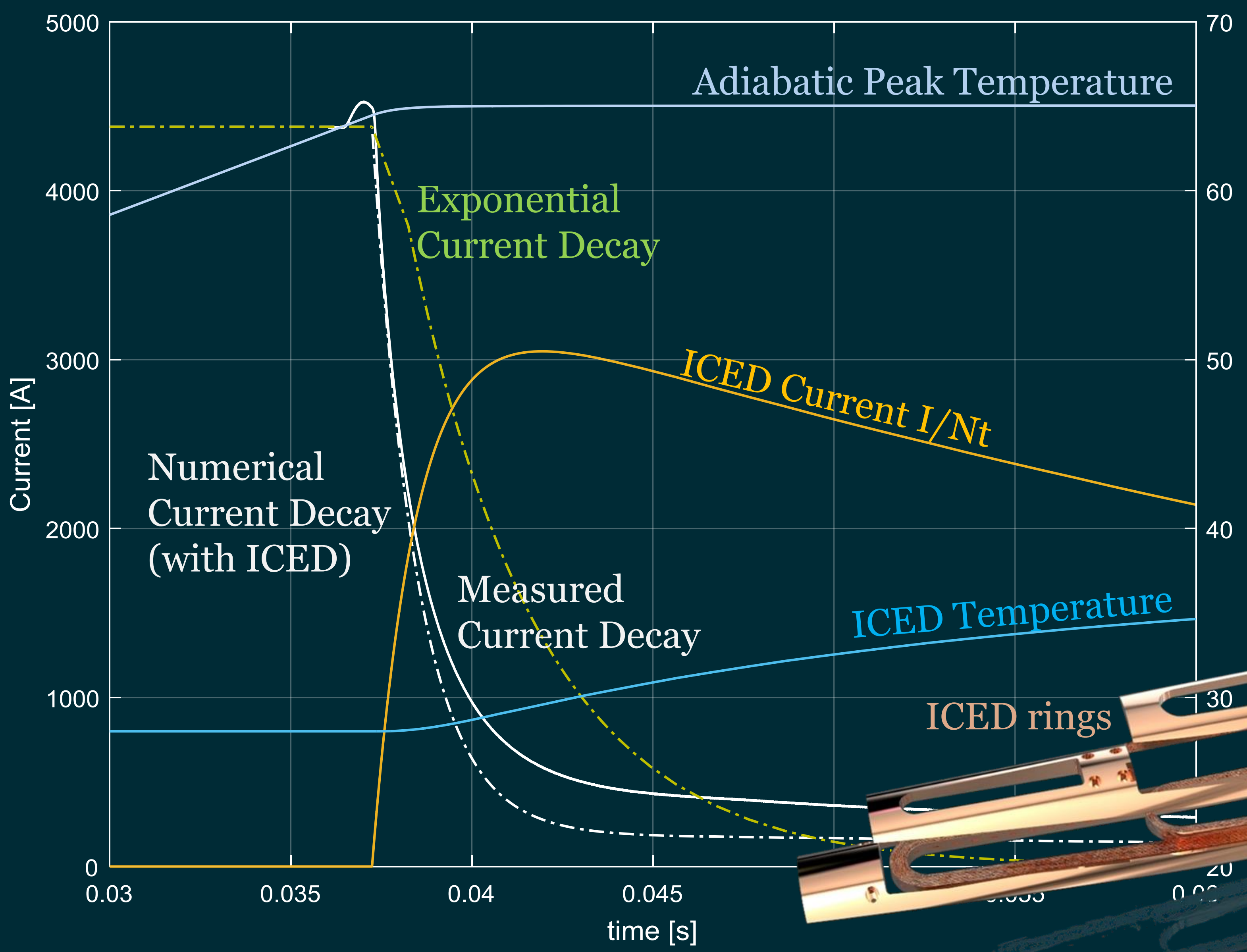
- The main coil is split up into N sections each protected by its own E3SPreSSO unit, which is connected in series
- The E3SPreSSO unit is:
  - A near-zero self-inductance superconducting circuit that can be turned normal (superconducting switch).
  - Located outside the main magnetic field:
    - Robust and cheap Nb-Ti or MgB_2
  - Or with parallel resistor non-stabilized ReBCO tapes.
- Allows for protecting large- or string of HTS magnet(s) which previously did not exist yet

E3SPreSSO



Looks like fault current limiter

Measured Current Decay during Dump

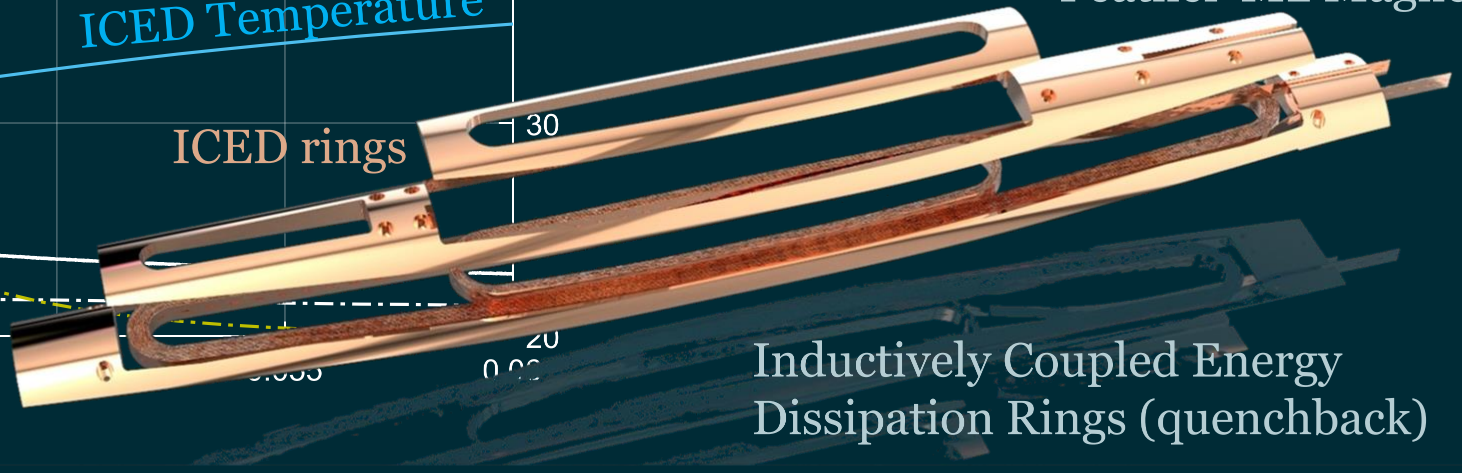


- Measured current decay is more similar to the numerical model with ICED than theoretical exponential decay.

- Conclusion
  - Part of the current is jumping into the ring when the protection is triggered: ICED works as expected.

Feather-M2 Magnet

ICED rings



Inductively Coupled Energy Dissipation Rings (quenchback)