Quench Antenna Development at Fermilab

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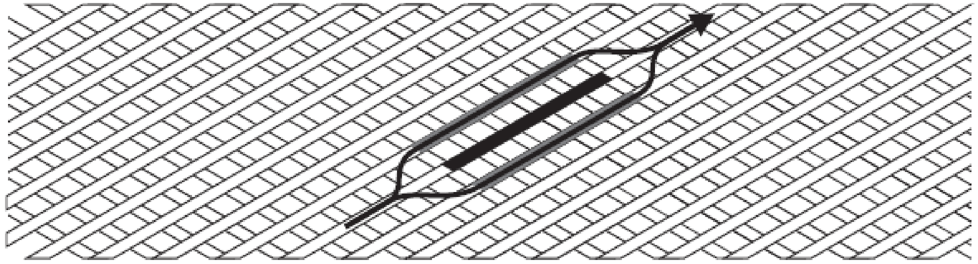
LDRD (Lab Directed R&D) award granted to develop new antennas that would provide complete coverage for quench detection (even in outer layers). These would be comprised of inductive pick-up loops etched onto flex circuitry that could be placed around and between coils.

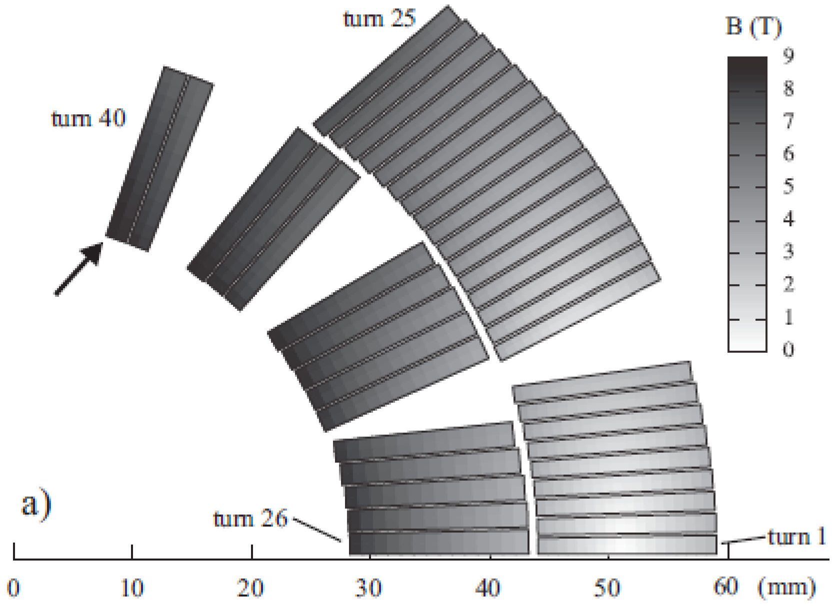
- Develop model for quench antenna and signal response to be able to inform design
- Verify model against data taken with existing antennas
- Develop design for new antennas

Current redistribution in quenching strand

Gerard Willering “STABILITY OF SUPERCONDUCTING RUTHERFORD CABLES FOR ACCELERATOR MAGNETS”, Ph.D. thesis, University of Twente

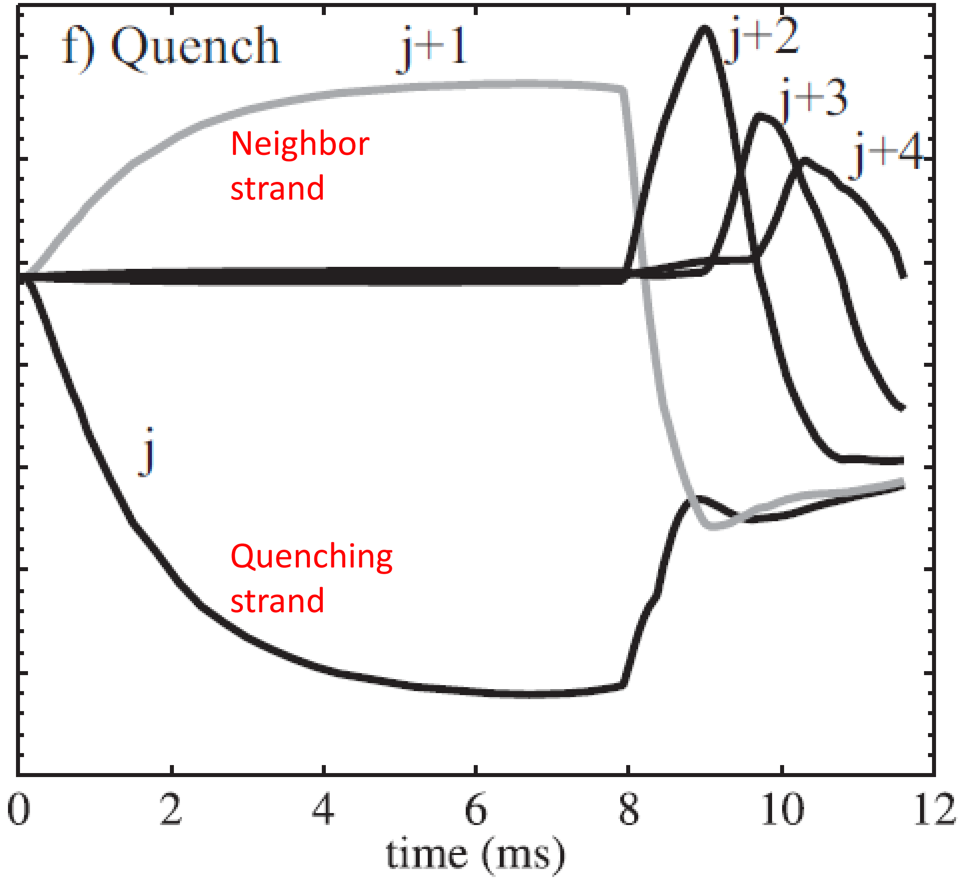


Current redistribution from a quenching strand

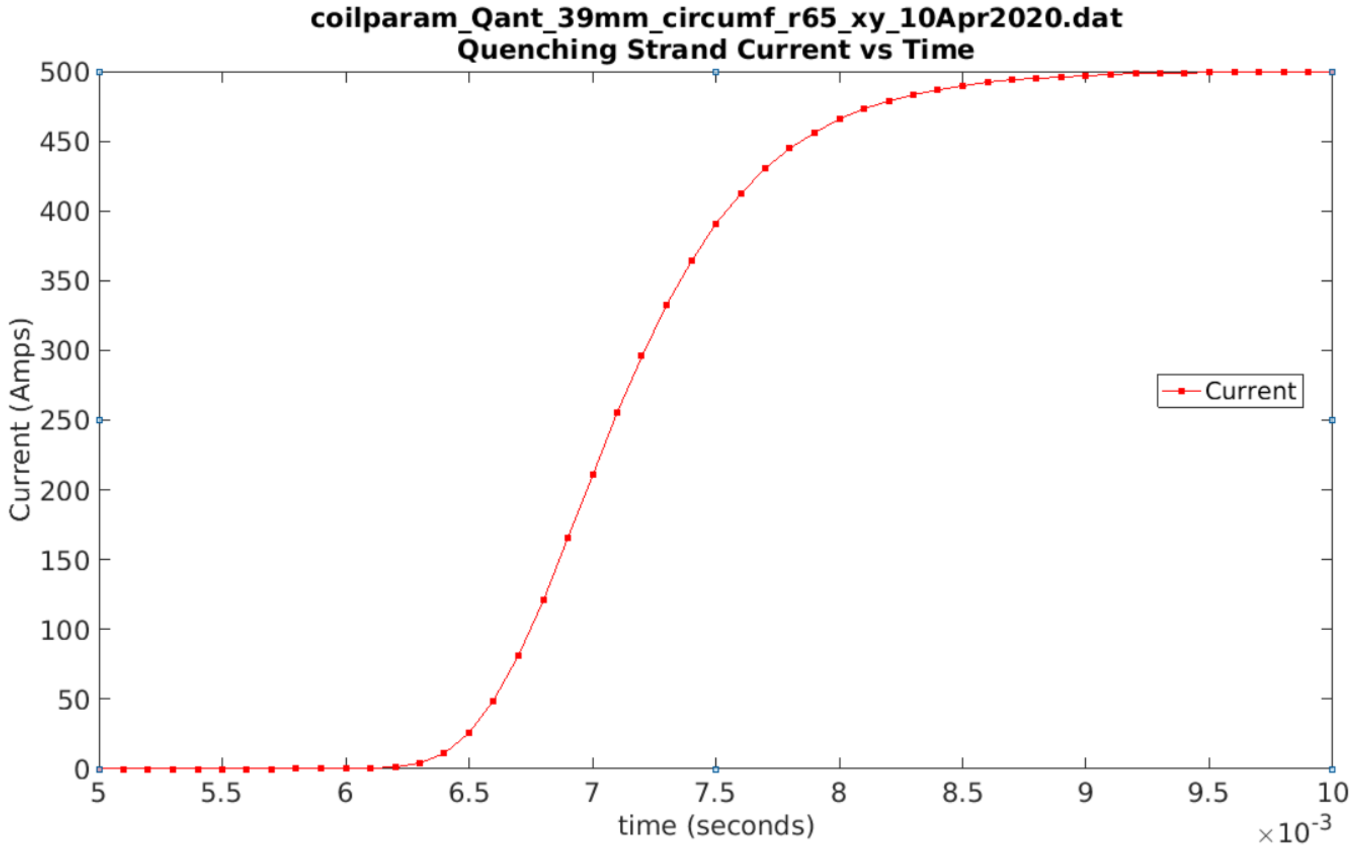


LHC magnet cross-section

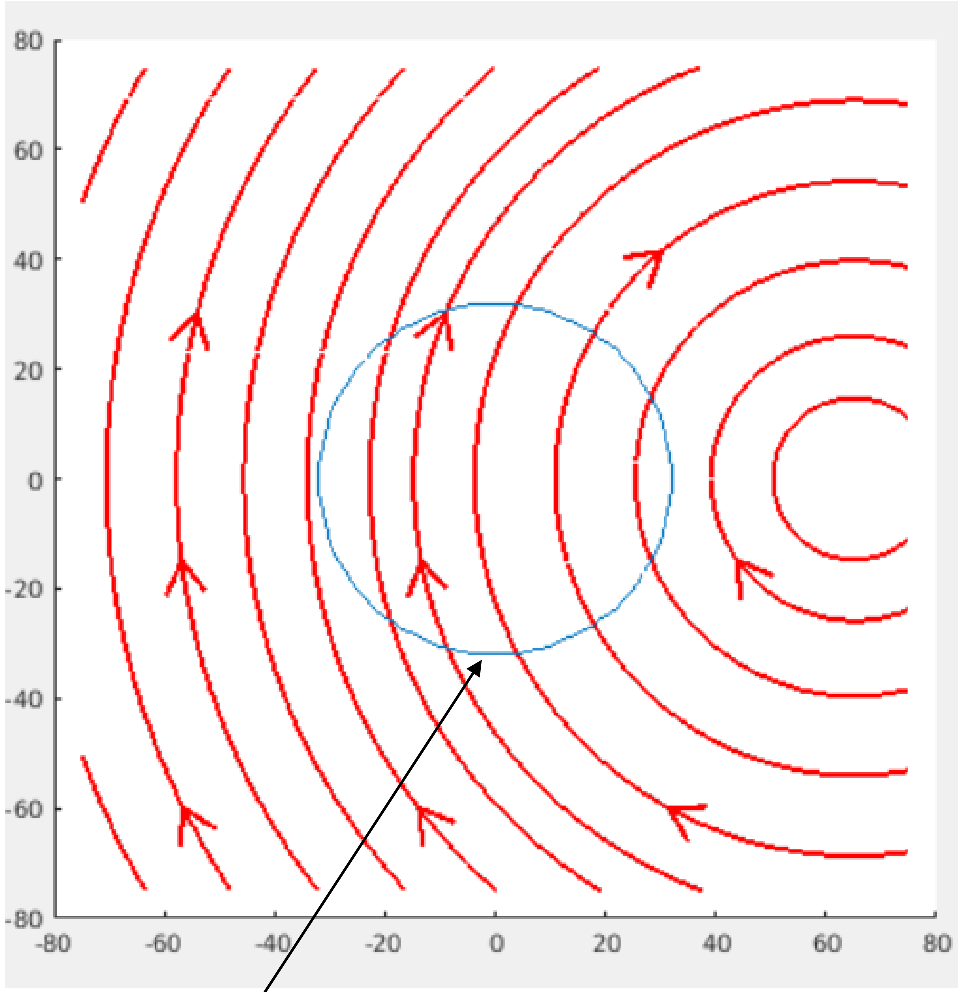
Model quench stranding as effectively negative current line appearing which cancels current in strand, and an additional current line in a neighboring location. If assume this occurs at an edge, then the distribution is radially outward.



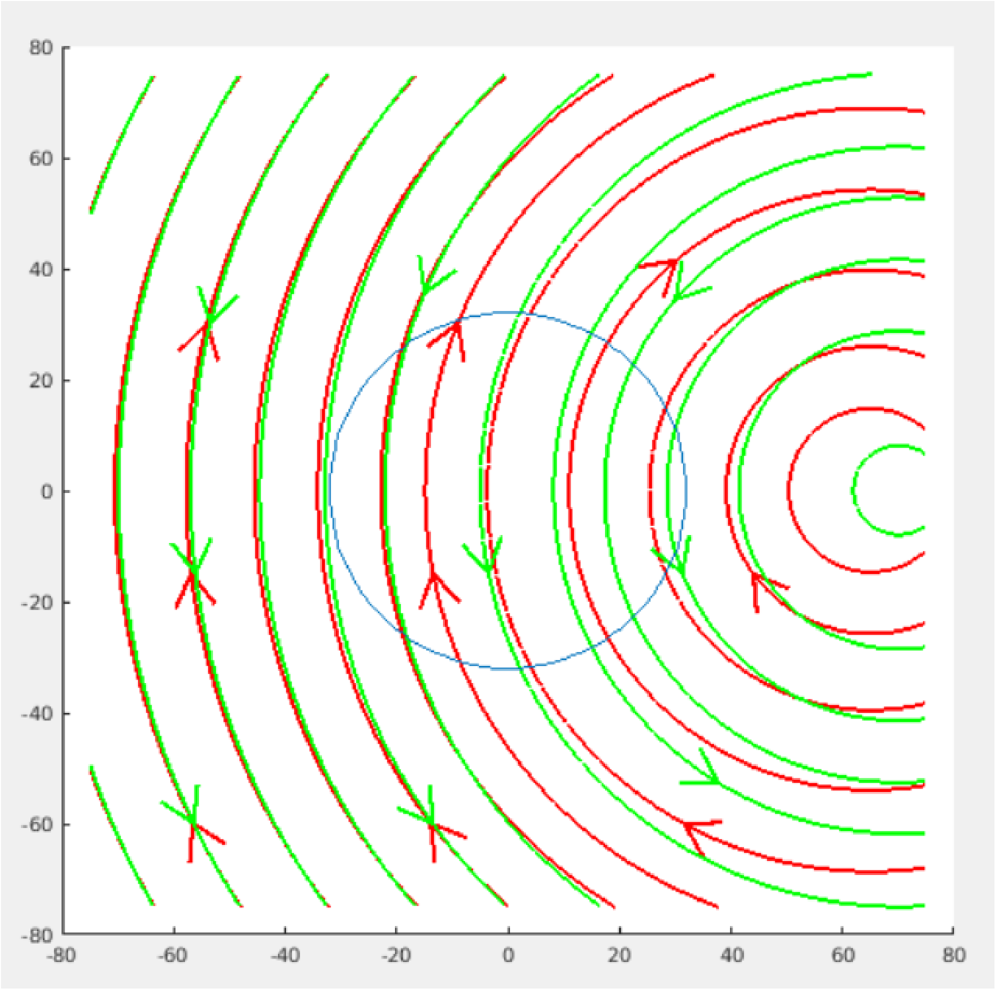
Simulated Quenching Strand
Current in Gerard's thesis



Quenching strand 'canceling' current used in QAnt simulation



Quench is modeled as current line at some distance and angle to the antenna (left), or as a current line doublet (right) – the doublet models the fact that current decrease in one part of the cable, causes redistribution to a nearby part.



64 mm Qant diameter is used

Can adjust parameters for

- Quench distance to antenna
- # of neighbors that current redistributes to
- the distance between quenching and redistributed strand

Current doublet gives better correspondence with measurement data and is used in the following

Short, flexible antennas have been used in the past for detecting quenches and have worked well.

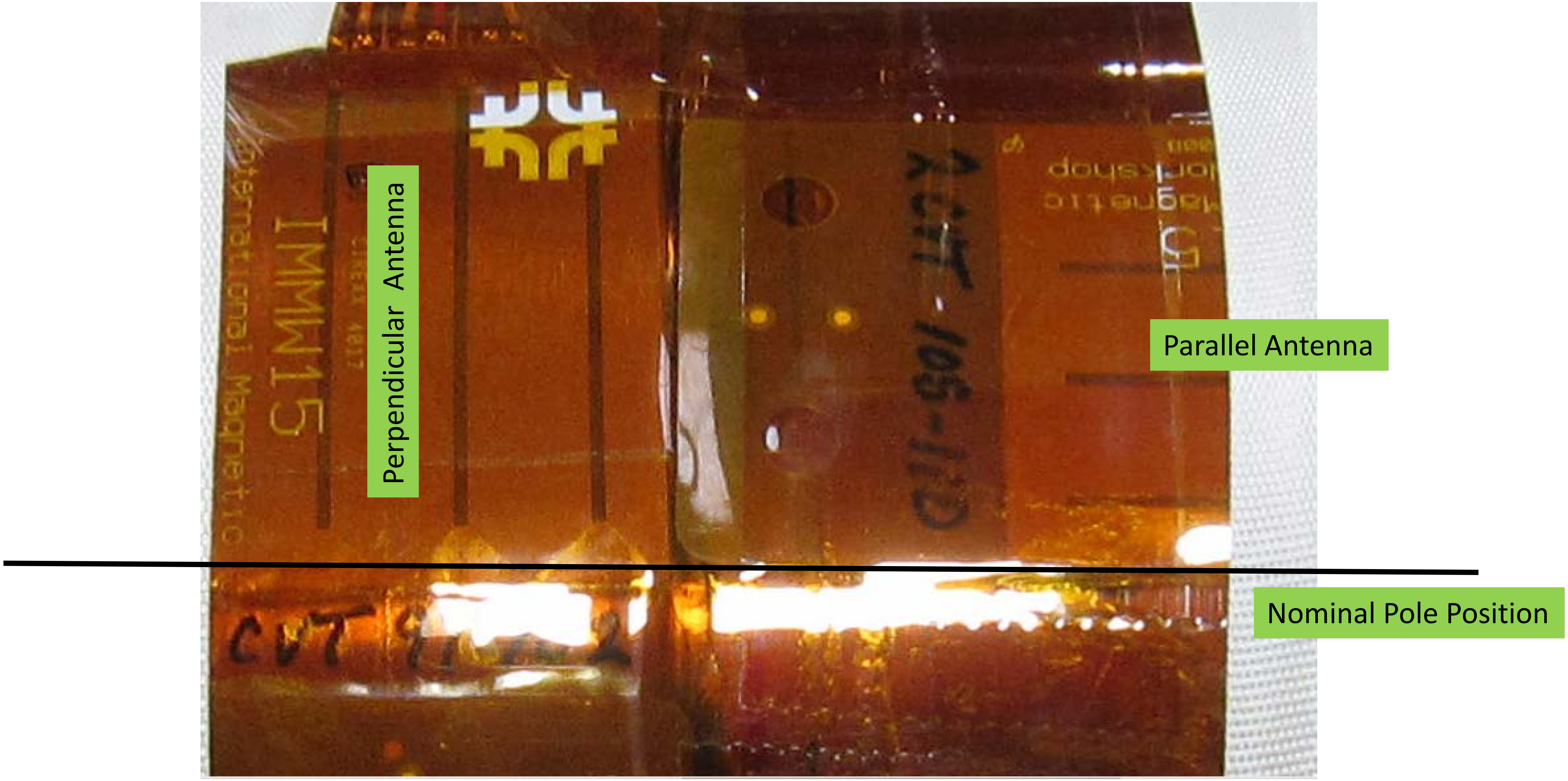
These are effectively radial magnetic measurement probes on a flexible substrate. They have a 4 parallel track structure, and when mounted in a radial configuration buck dipole and quad fields.

UB is the ‘UnBucked’ signal from track1, DB is DipoleBucked from track 1 – track 3, and DQB is Dip/QuadBucked from (track 1 – track 3) – (track 2 – track 4)

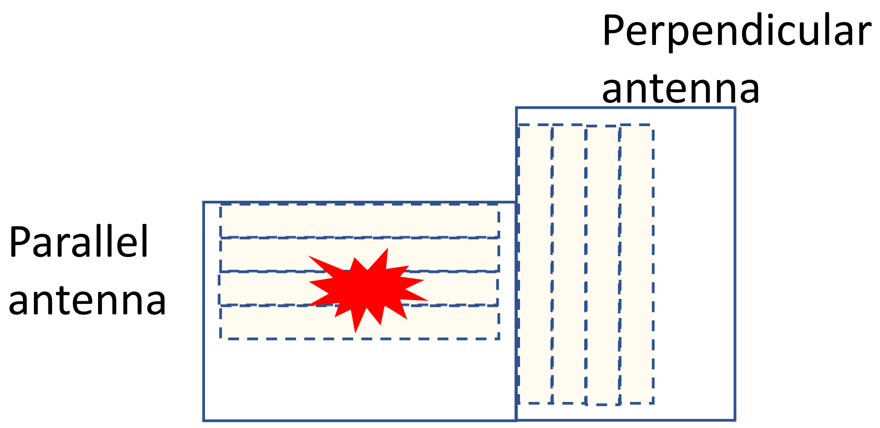
32mm wide Quench Antenna:
2018 Flex PCB with 4 tracks, 36 turns per track

Experimental validation

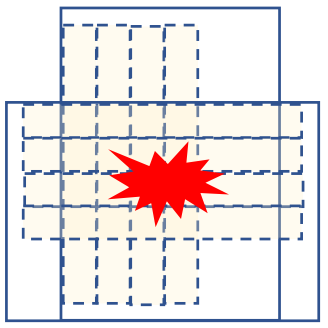
MQXFS1d/e short model quad had well known quench location – quench antennas were mounted nearby for testing



In the MQXFS1d Qant data, the perpendicular antenna data signals are in the noise, while the parallel antenna is always seen and has signal size of about 5mV. See if simulation matches these results:



Original (mqxfs1d) orientation

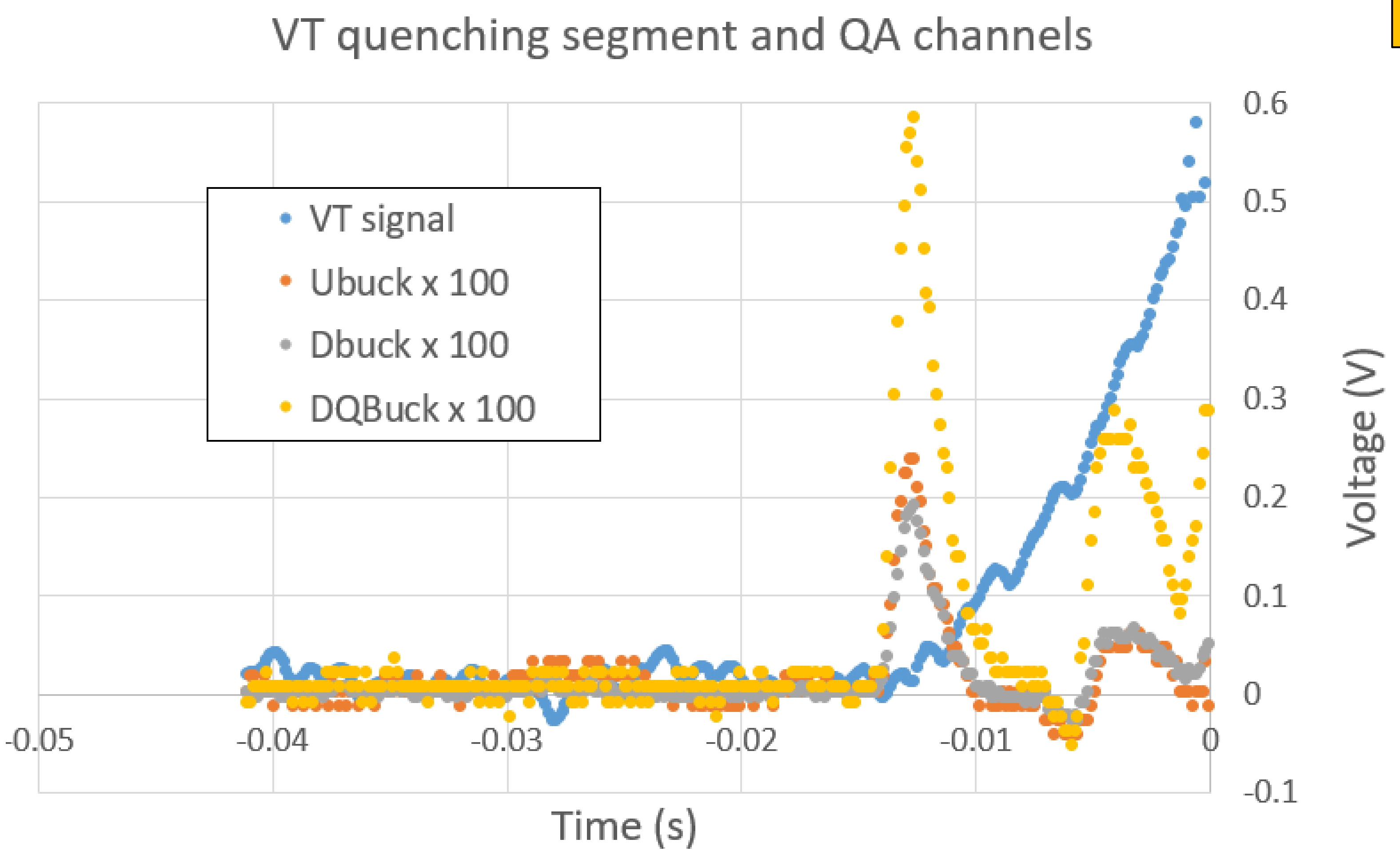


mqxfs1e orientation

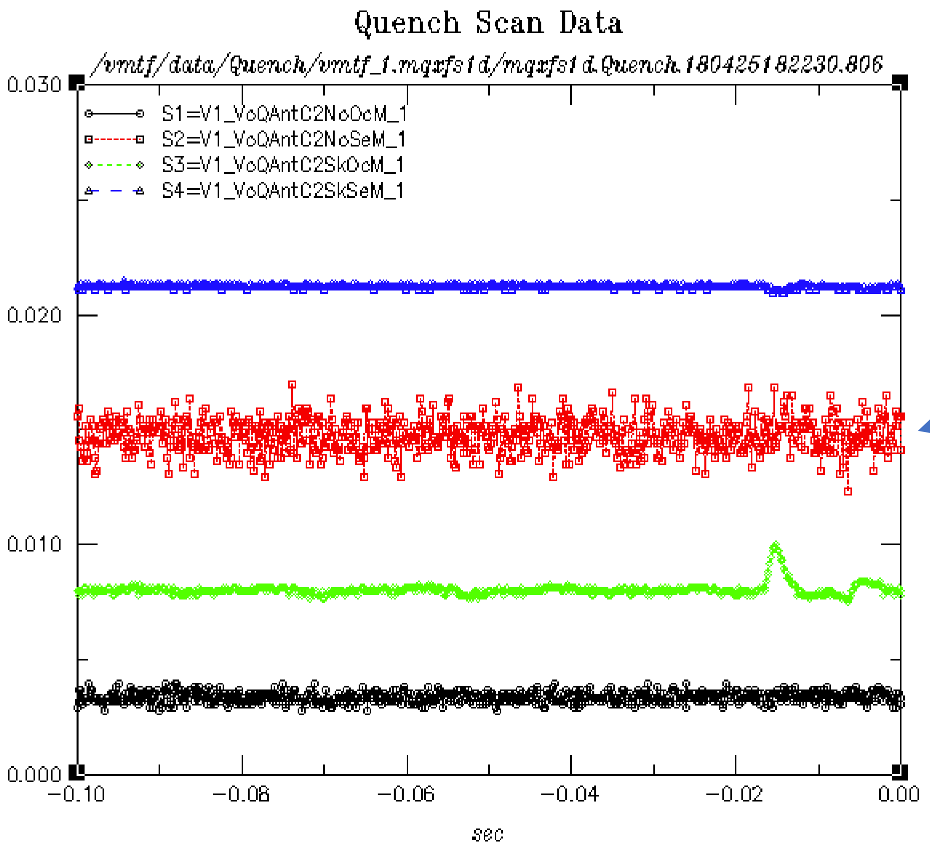
Parallel antenna signals had large clean signals which matched voltage tap response

Actual Qant data (x100):

- DQB ~2.5x larger than UB
- UB slightly larger than DB
- Signs same on all signals

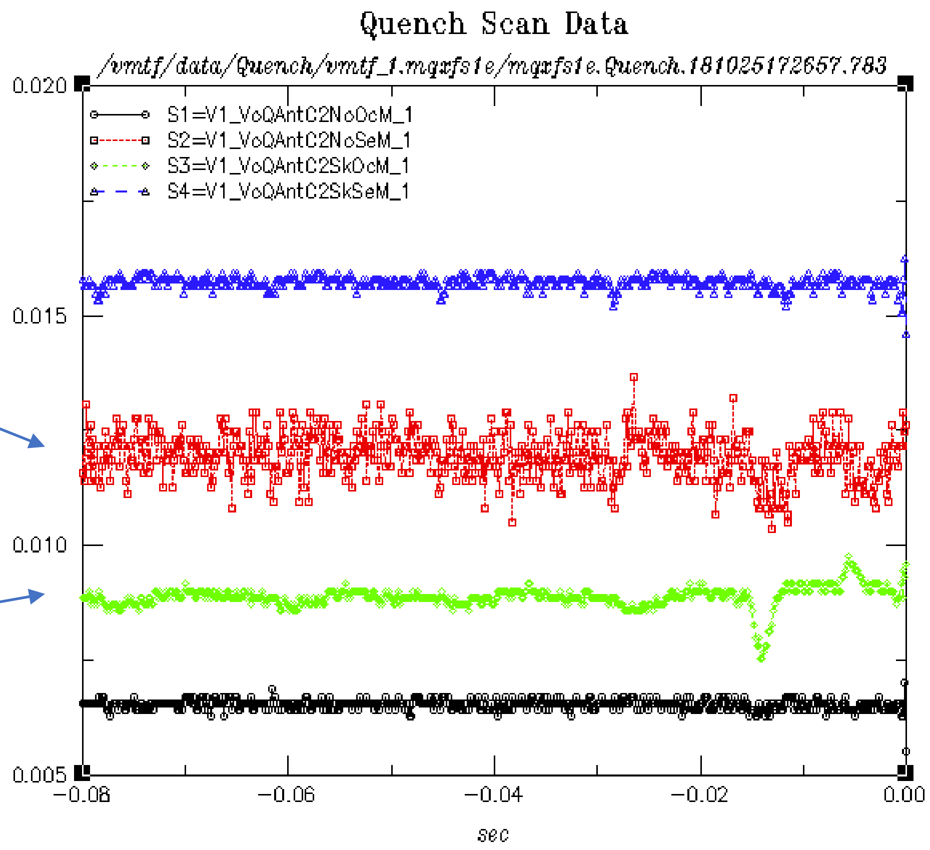


Note that get max voltage in ~1.2ms



Perpendicular antenna UB

Parallel antenna DQB



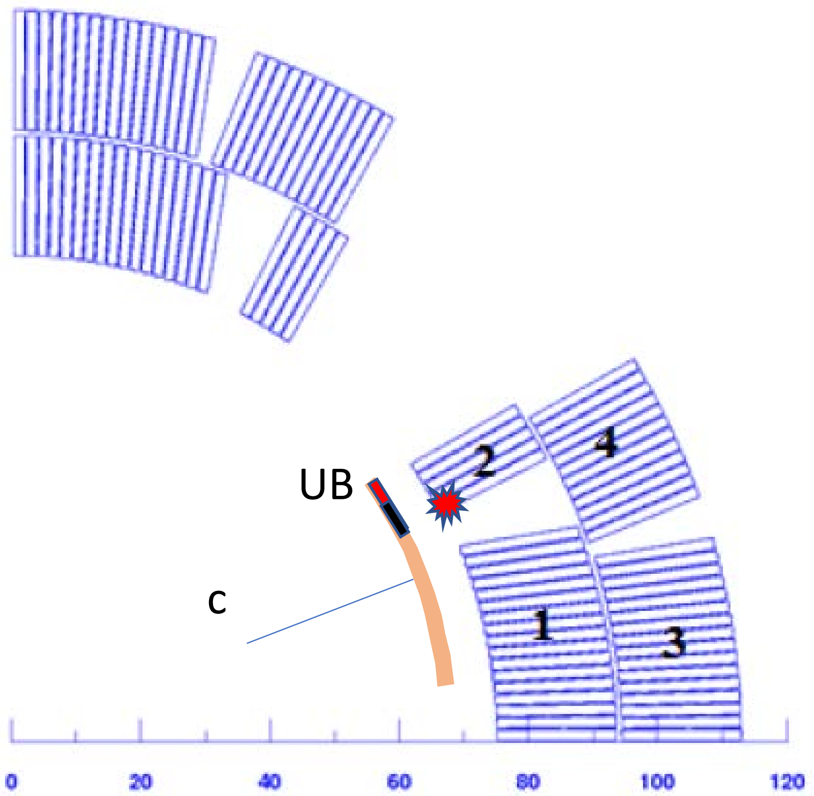
MQXFS1d

The perpendicular antenna has no real response

MQXFS1e

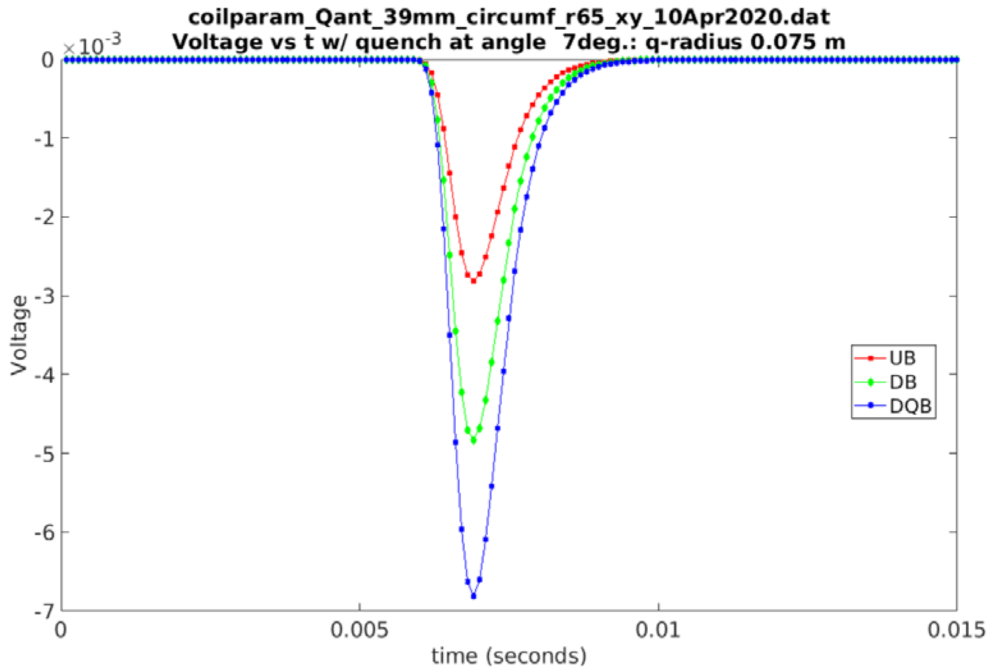
The perpendicular antenna now has some small response

Parallel antenna, quench_radius = 75mm



Using 1.8mm as cable thickness

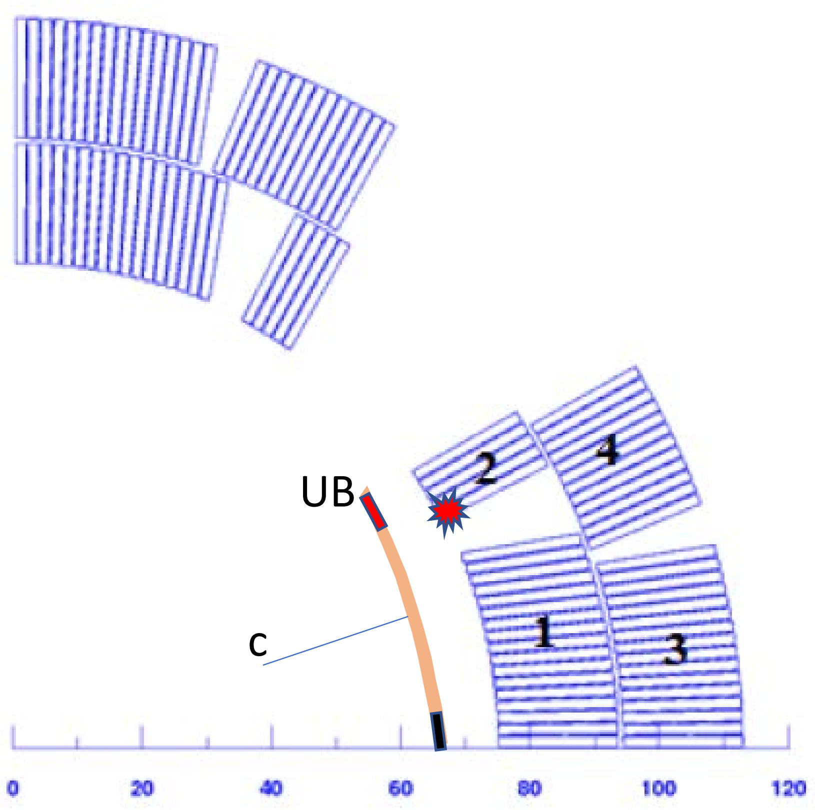
Quench antenna is rotated 0 deg from nominal daq position



“parallel” Qant case: Quench is effectively at ~ +7 deg

➔ DQB signal is near (negative) max at this angle (-6.7e-3) ✓
➔ DQB signal ~2.5x larger than UB ✓ (UB -2.6e-3, DQB about 2.6x)
➔ UB amplitude little larger than DB ✗ (DB ~-4.5, 1.7x larger than UB)
➔ Sign of UB and DB are same as DQB ✓

Perpendicular antenna, quench_radius = 75mm

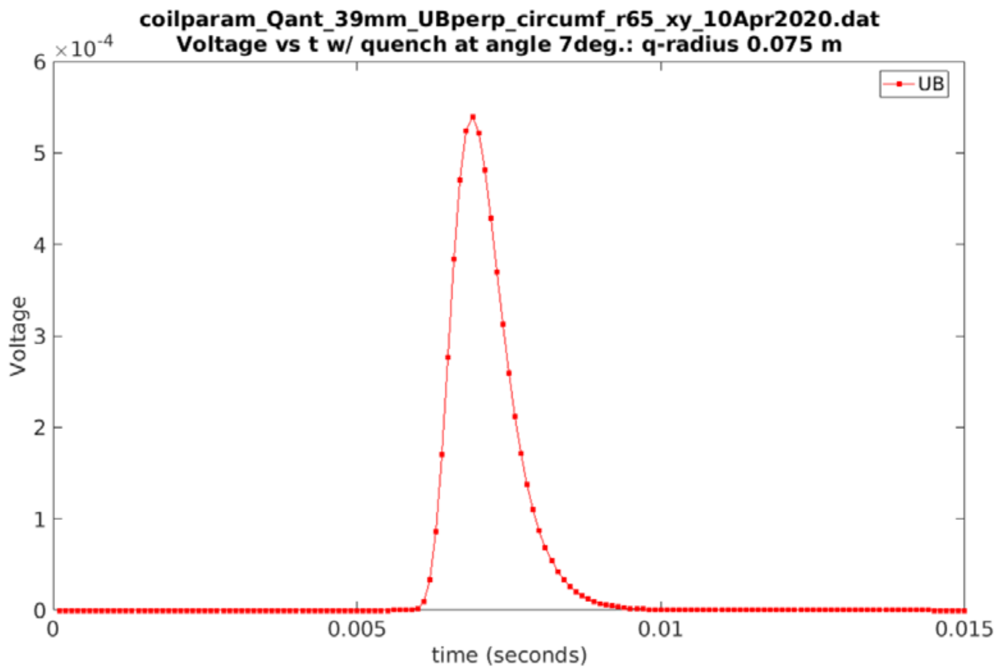


"perpendicular" Qant case: Quench is effectively at ~ 10 deg

➔ UB amplitude 5.3e-4 ✓ factor 10 smaller than parallel signals

Using 1.8mm as cable thickness

Quench antenna is rotated 0 deg from nominal daq position

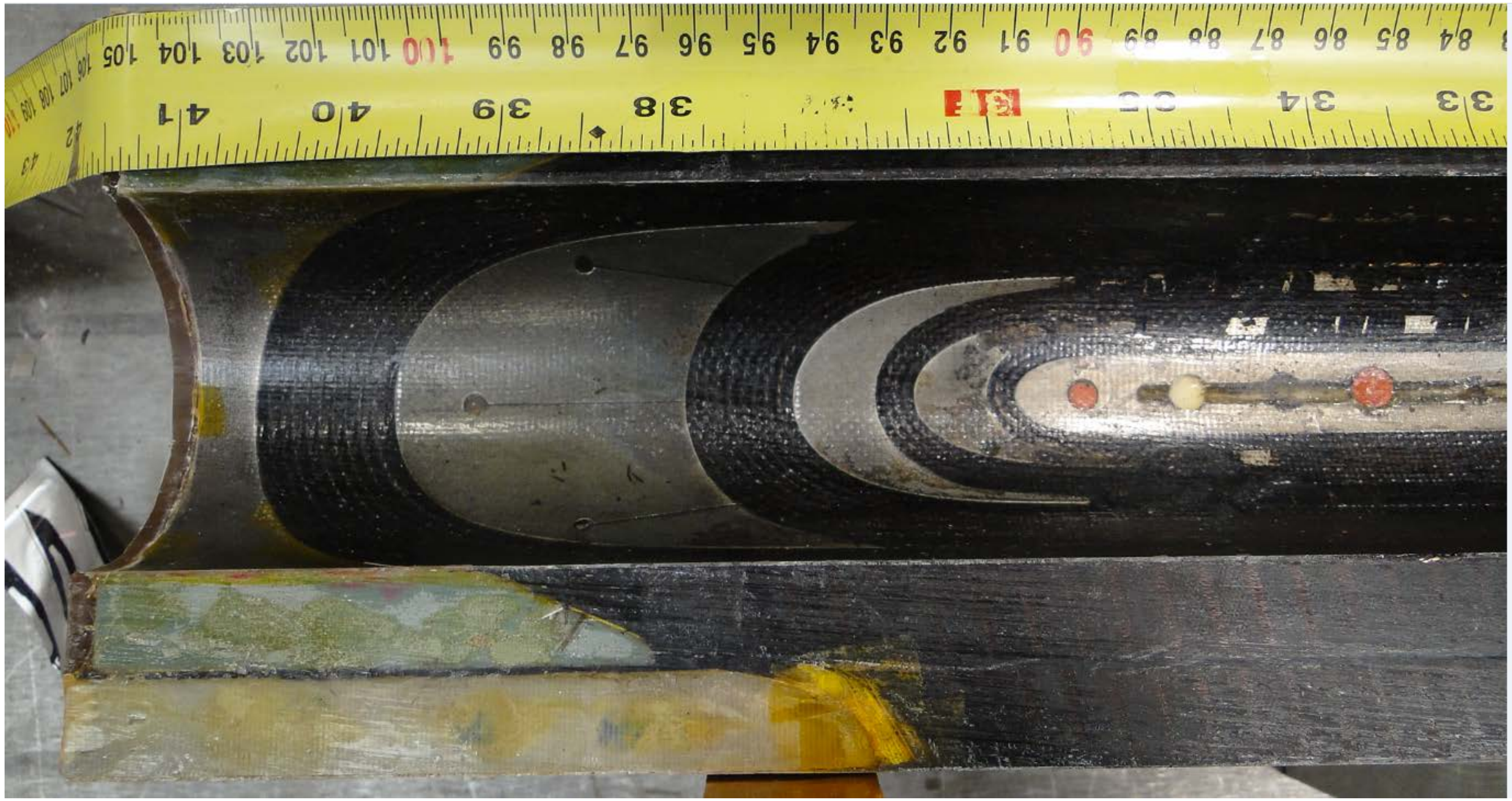


Simulation model recreates fairly well the response (including magnitude) of the experimental quench antenna voltage signal data (both parallel and perpendicular) taken at known quench location on MQXFS1.

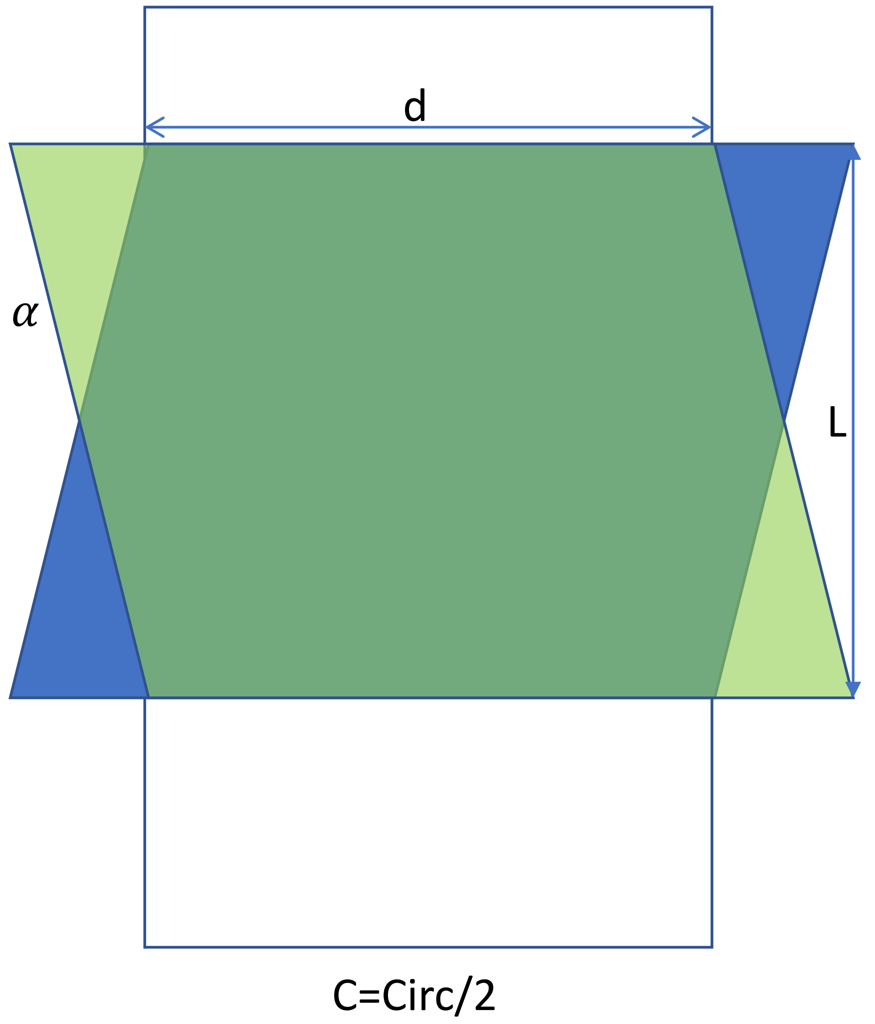
➔ Some confidence in going forward with new designs!

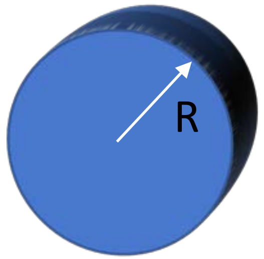
First new design is for 1m long magnet with 65mm aperture.

This is actually a “mirror magnet” (single coil in iron structure), so will need a roughly half-cylinder shape antenna for the aperture.



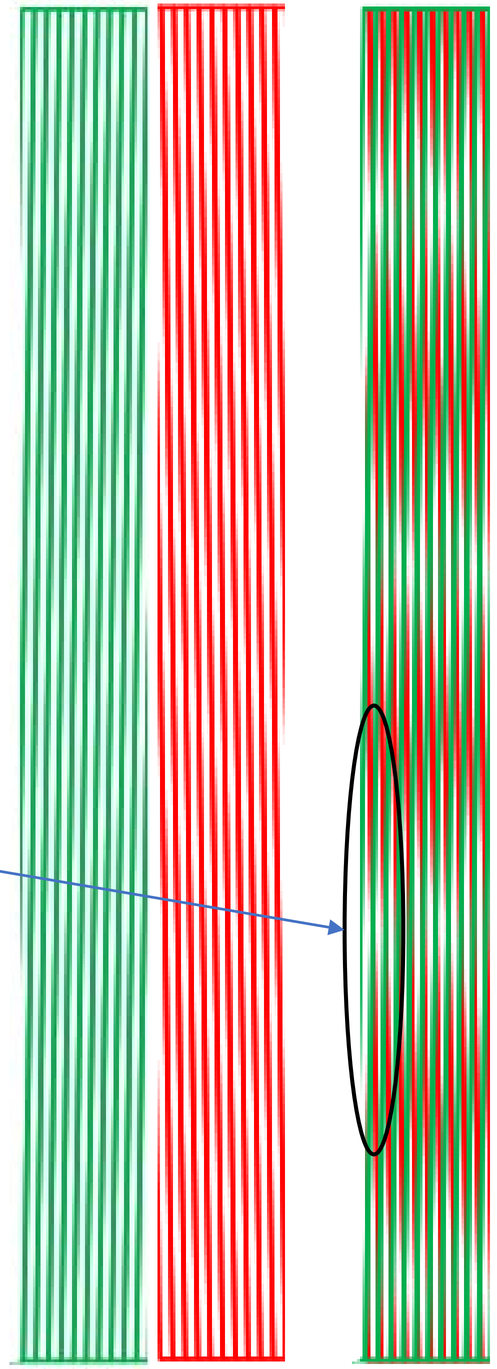
Mirror magnet QAnt design #1





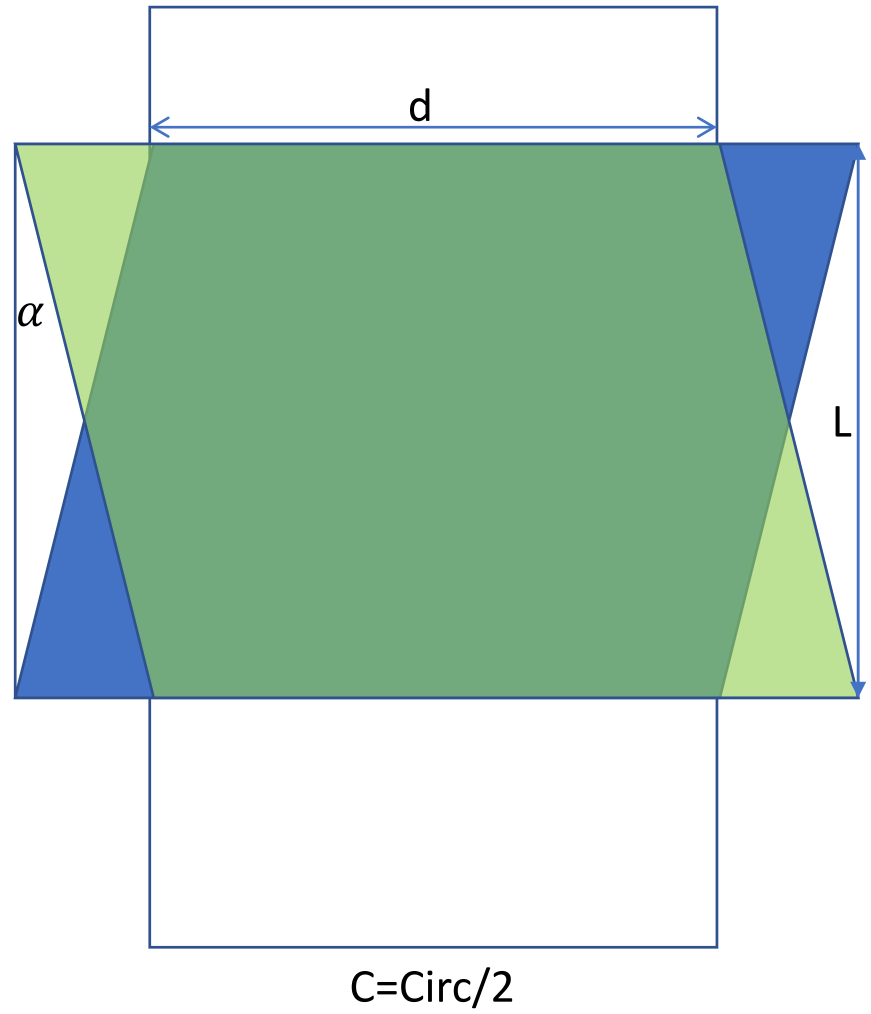
L=1000mm
R=30mm
W=9.42mm
C=Circ/2=94.25mm
Nch_x=13
Alpha=0.028rad (1.5 degrees)
pixelHeight=333mm
d=94mm

Nch_x_tot=26 (2 panels)



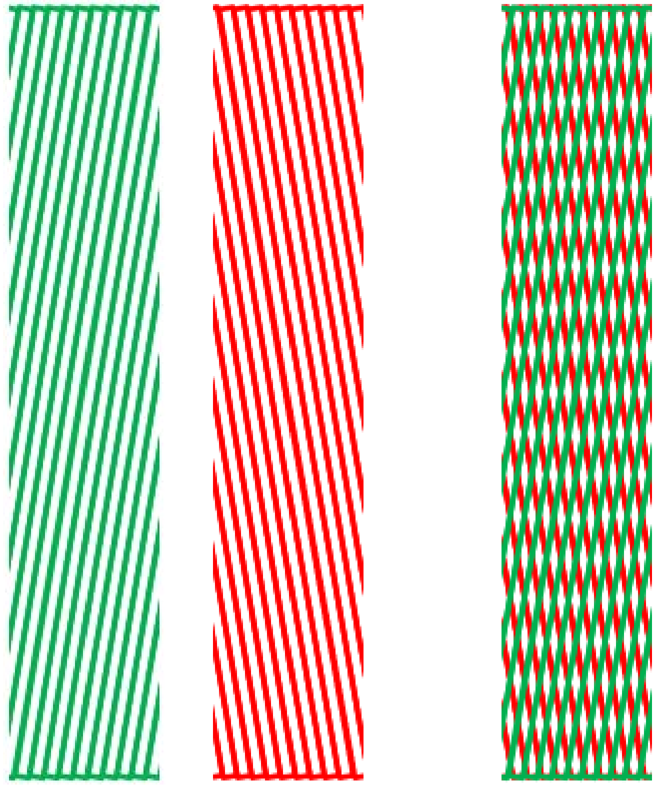
Very shallow angle➔ large ‘pixel’ length

Mirror magnet QAnt design #2



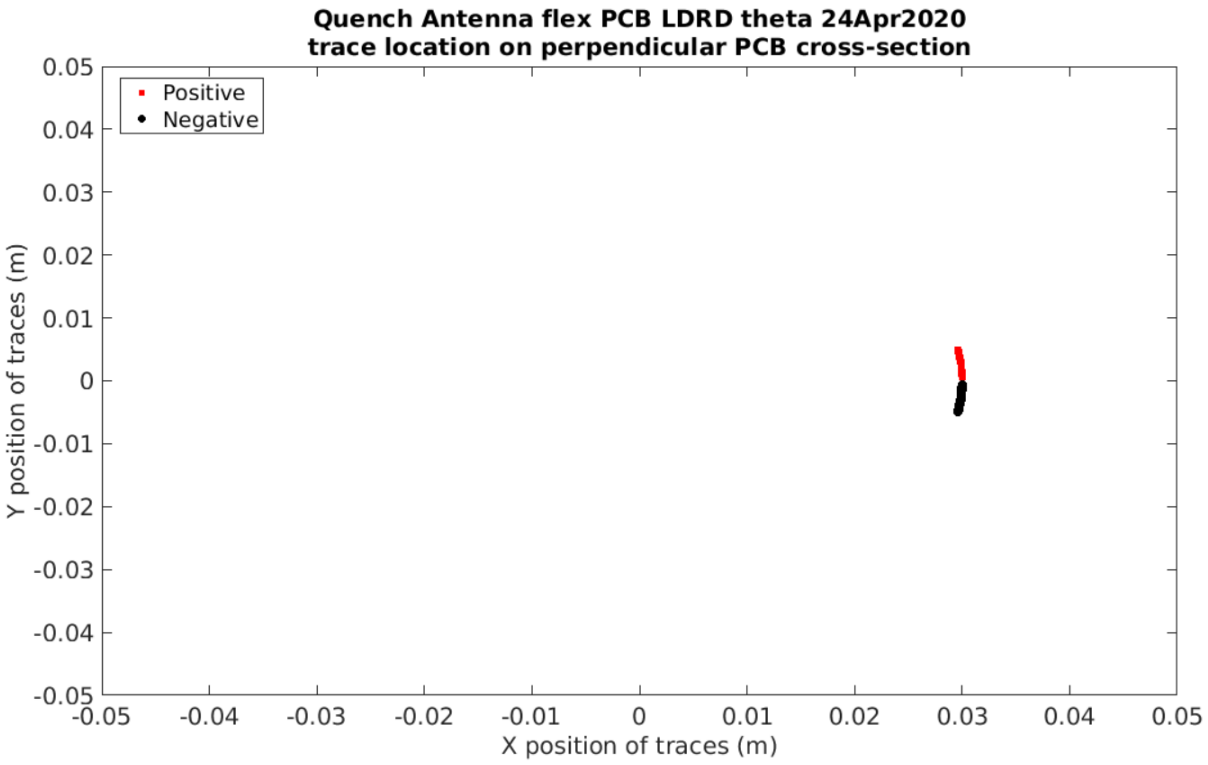
L=500mm
R=30mm
W=9.42mm
C=Circ/2=94.25mm
Nch_x=10
Alpha=0.175rad (10 degrees)
pixelHeight=51mm
d=94mm

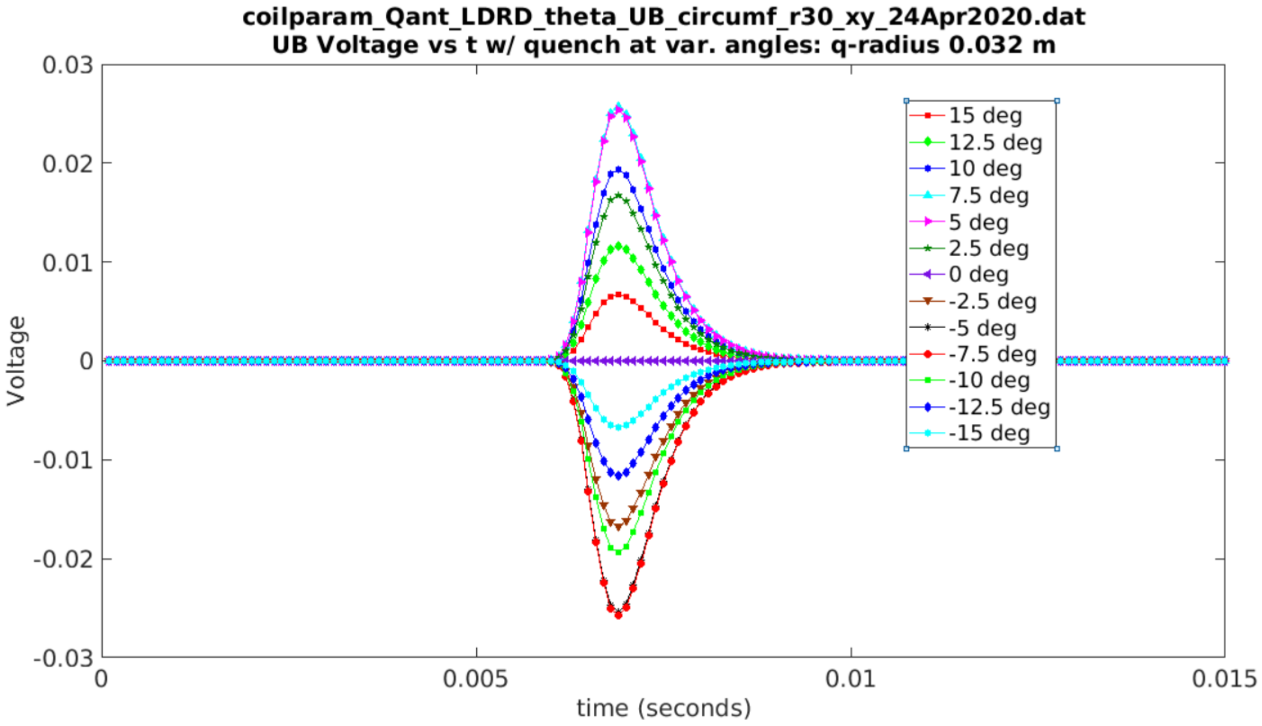
Nch_x_tot=80 (10 at each end per panel → 40, but then need 2 sets to get to 1m length)



less shallow angle → smaller 'pixel' length but need more channels

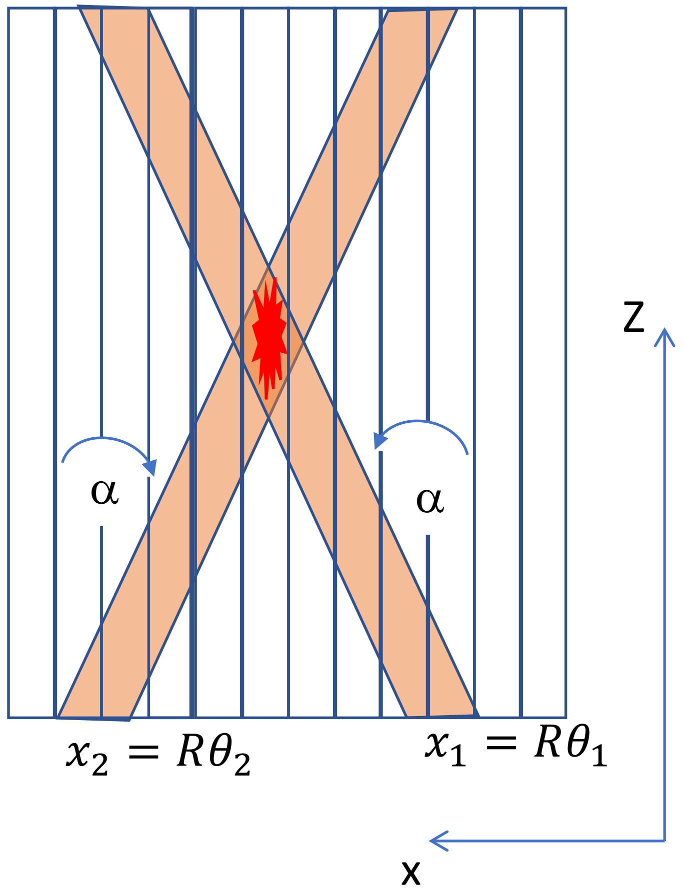
First simulate straight long 10mm wide loop, assume can fit 10 , with traces separated by 0.4mm (get about 12 turns), placed wrapped on 30mm radius cylinder





Large signal – quench is very close to antenna

Extent of antenna is +/- 5mm , so if had series of antennas side by side, the next center would be at theta=10/R radians. R=30➔ theta separation is ~19 degrees (0.333 rad)



Use intersection of determined quench angle/x-position from each of the two panels to locate quench.

$$x_Q = \frac{x_1 + x_2}{2}$$

$$z_Q = \frac{\alpha}{2} * (x_2 - x_1) \quad \text{or} \quad z_Q = \frac{R * \alpha}{2} * (\theta_2 - \theta_1)$$

- For example, for design with 1.5 degree panel angle, have 1000mm long panel, 13 channels per panel and expect resolution of about 333mm from the pixel height, or if signals good enough, about $\sqrt{2} * 20$mm in z location of quench from using ensemble.

- For 10 degrees panel angle, both resolution methods increase by about a factor 7

Summary

A simulation for the response of induction-loop quench antennas has been developed which allows for the exploration of various geometries and configurations of quench antennas and quench development.

The simulation has been validated at some level using experimental data from MQXFS1d/e where the quench location and location of quench antennas was well known.

A couple of new proposed configurations for full-coverage quench antennas that will be developed and tested was shown, along with some analysis of localization resolution.