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FERMI NATIONAL ACCELERATOR LABORATORY

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# A dedicated mirror-magnet experiment to study quench characteristics and dependencies in $Nb_3Sn$ coils and explore improvements of diagnostics capabilities

**Stoyan Stoynev (FNAL)**
for the FNAL team (Maria Bal., Joe DiM., Steve K., Mike K., Rodger B., Fred N., Giorgio A.,…

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Heavily instrumented coil is a key for this “experiment”

# Outline

The bad news: we have not managed to test the magnet yet

The good news: we are on the final stretch of magnet assembly

## All at a glance

How does it look what we are preparing

## Studies to target

Why we are doing it

## Instrumentation in place

Our eyes and ears (and more)

# “Mirror-magnet experiment”: a test vehicle for magnet diagnostics and more

We wanted to do this for many years now* but had to work within priorities

Quench characterization by environmental control (tunable array of spot heaters); over-instrumentation of the whole coil – quench antenna arrays, optical fiber mesh, acoustic sensors in close proximity to quenching; other non-invasive techniques; experimenting with new arrangements (QA arrays, fiber mesh); supporting modeling of processes/physics; influencing quench training ($QCD_{evice}$)

*FERMILAB-FN-1117-TD, https://lss.fnal.gov/archive/test-fn/1000/fermilab-fn-1117-td.pdf

# The initial plan

We are mostly following it

- Take an existing, never used before, coil (#06, from MQXFS series)
- Instrument it “well” (as you will see) to serve the needs and goals
- Assemble it as part of a “mirror” magnet (MQXFSM03)

Crucially, this would be the third version of already built mirror-magnets, no change in parameters*

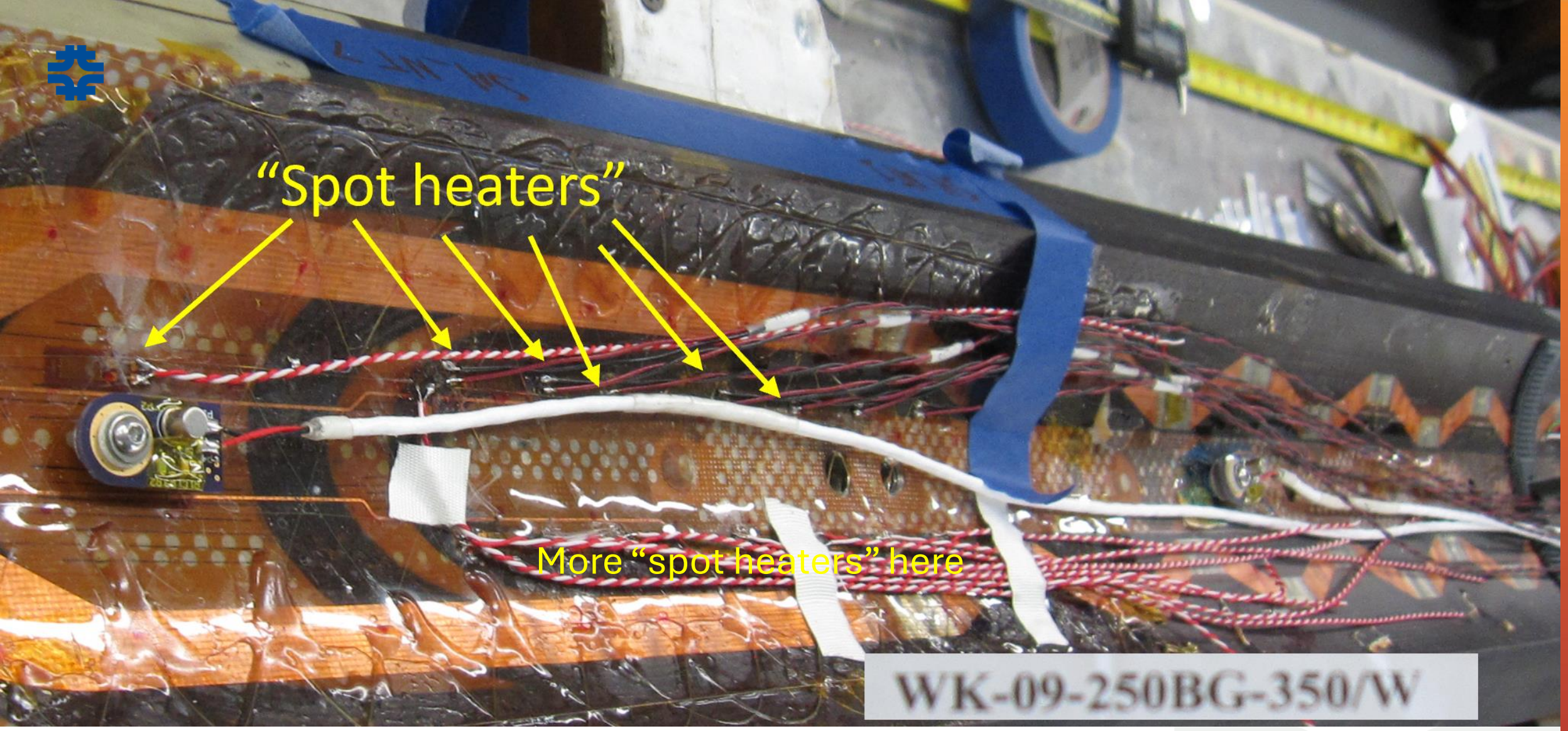
- Finalize instrumentation on the magnet
- Prepare for testing
- Test
- Analyze

**How much time could it take?**

*FERMILAB-TD-15-018, https://larpdocs.fnal.gov/LARP/DocDB/0010/001087/001/MQXFSM1_test_summary_TD-15-018.pdf

# Environmental control

Critical for evaluation of many expected results

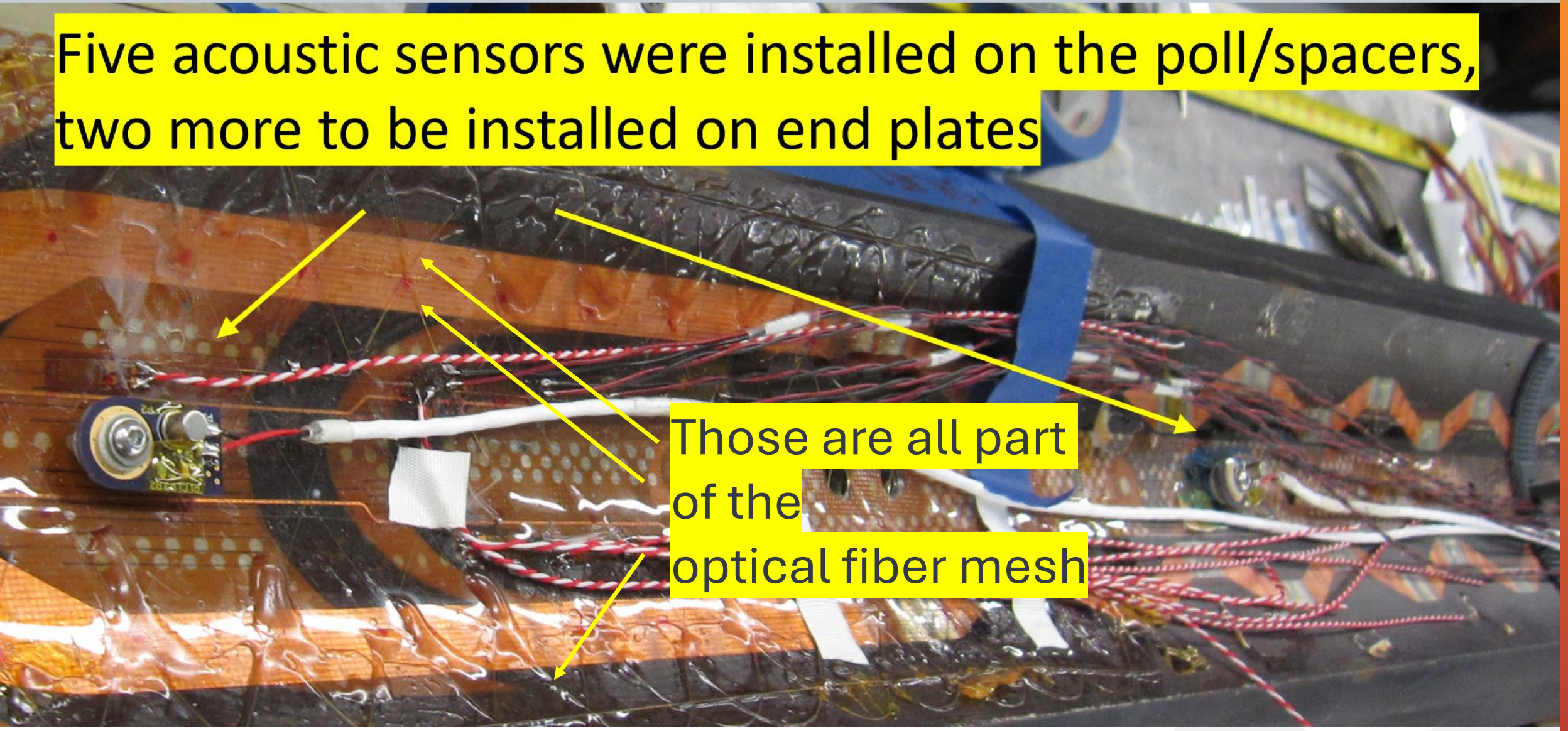



## Each of the spot heaters can be controlled separately or in groups

This allows to "pre-condition" the area of induced quenches and observe voltage behavior, among other sensors

# Observe at close proximity

Critical for obtaining the data quality we need

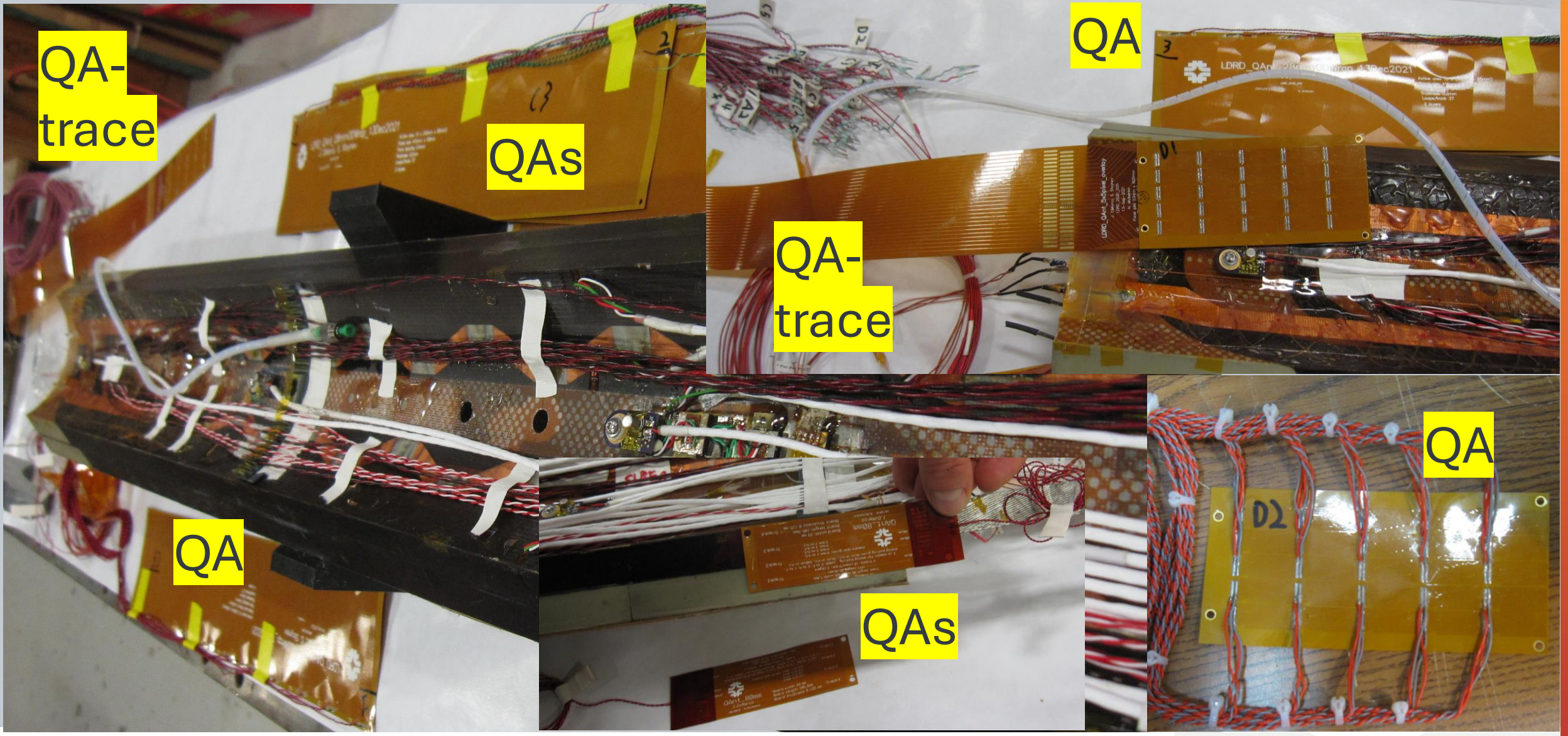



## Stress and mechanical events/evolution in near 3D picture

Acoustics can be taken at 1 MHz, optical fibers at three-four orders of magnitude down

# More over-instrumentation

Quench antennas are highly non-invasive




## Quench antenna (QA) arrays are to play an oversized role in the experiment

Including ~ six “new” separate panel designs; will cover the whole inner surface and $Nb_3Sn$-NbTi splices

# Studies targeted

More details are available*

- QCD test after the first quenches (see next)
- Correlate observable signals in quenches and ramps – QA, acoustics, optical fibers, VTs
  - Input for ML/AI methods, in development
- Explore multi-dimensional optical-fiber information on stress development
  - Similar for QA
- Experiment with controllable quench propagation and observables
  - The array of spot-heaters
- Compare (match?) controllable induced quenches with spontaneous quenches
  - In particular – voltage tap (VT) signals
  - The coil has 15 VT segments, including two splices
- Deduce current redistribution, determine the role of splices – (all QAs and VTs)
- Develop and improve modeling based on data

*FERMILAB-FN-1117-TD, https://lss.fnal.gov/archive/test-fn/1000/fermilab-fn-1117-td.pdf

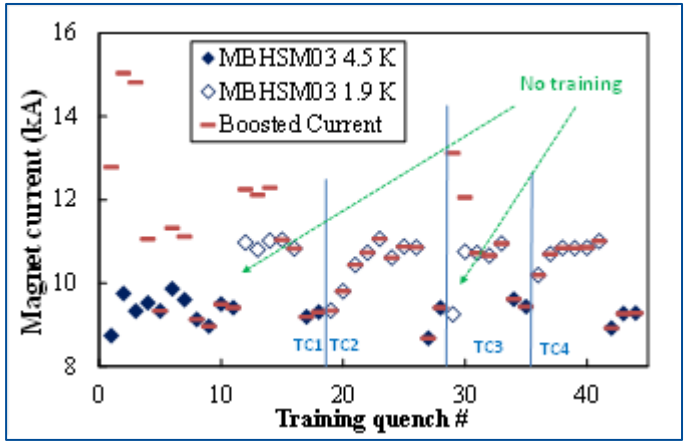
# Quench Current-boosting Device (QCD)

It boosts magnet current long enough to affect training

The original plan was to test QCD on two different coils (magnets)

- The first test was done in spring of 2022*
  - Despite some coil non-conformities, the QCD test was successful
  - Training in the (dipole) coil was repeatedly avoided with QCD in use
- The second QCD test is part of the “mirror magnet experiment”
  - A (quadrupole) coil, never used before, was chosen
  - It is also one of series (QXFS) for which we have consistent training data
  - We started coil instrumentation and magnet preparations in 2022
- In the meantime, the conclusion from QCD and earlier studies stipulating that CLIQ should also affect training was confirmed**
  - There was later an explicit/direct test at CERN as well
- In essence – 10-20 ms or more of overcurrent affects training


QCD at FNAL




Training with and without QCD

*S. Stoynev, M. Baldini and S. Feher, "Commissioning, Performance, and Effect of the Quench Current-Boosting Device on a Dedicated Superconducting Magnet," in IEEE Transactions on Applied Superconductivity, vol. 33, no. 5, pp. 1-6, Aug. 2023, Art no. 4702406, doi: 10.1109/TASC.2023.3261264.

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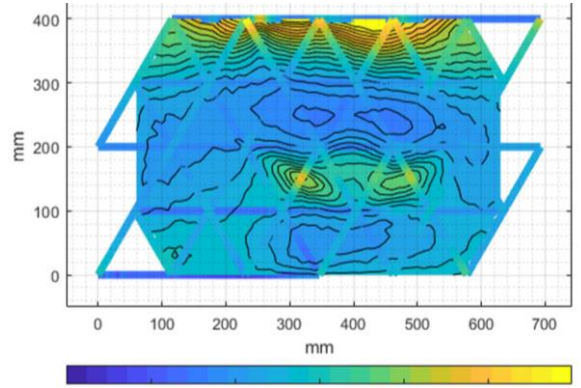
# Instrumentation development

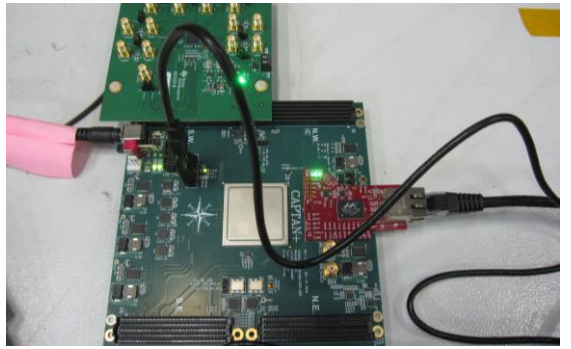
Another major reason we want to perform this “experiment”

- Optical fiber mesh has demonstrated its unique capabilities
  - We really want to take data close to flowing current and quenches
  - Most tests were on the skin of magnets
  - Investigating and testing options to reduce breaking accidents
- The zoo of Quench Antenna designs is still to be vetted
  - We showed pros and cons for some of them*
  - But we are still no explore all in real magnet tests, make improvements
- Current/power supply spikes
  - With sensitivity of ~ 5 mA or better those data provide excellent support for comprehensive investigation of ramp/quench data
- DAQ system development
  - This “experiment” was always about testing innovative approaches
  - We are developing a DAQ system to unify our data taking experience and capabilities, including real-time processing (with AI-ML algorithms in mind)




Strain map snapshot*


AC current clamp installed at VMTF

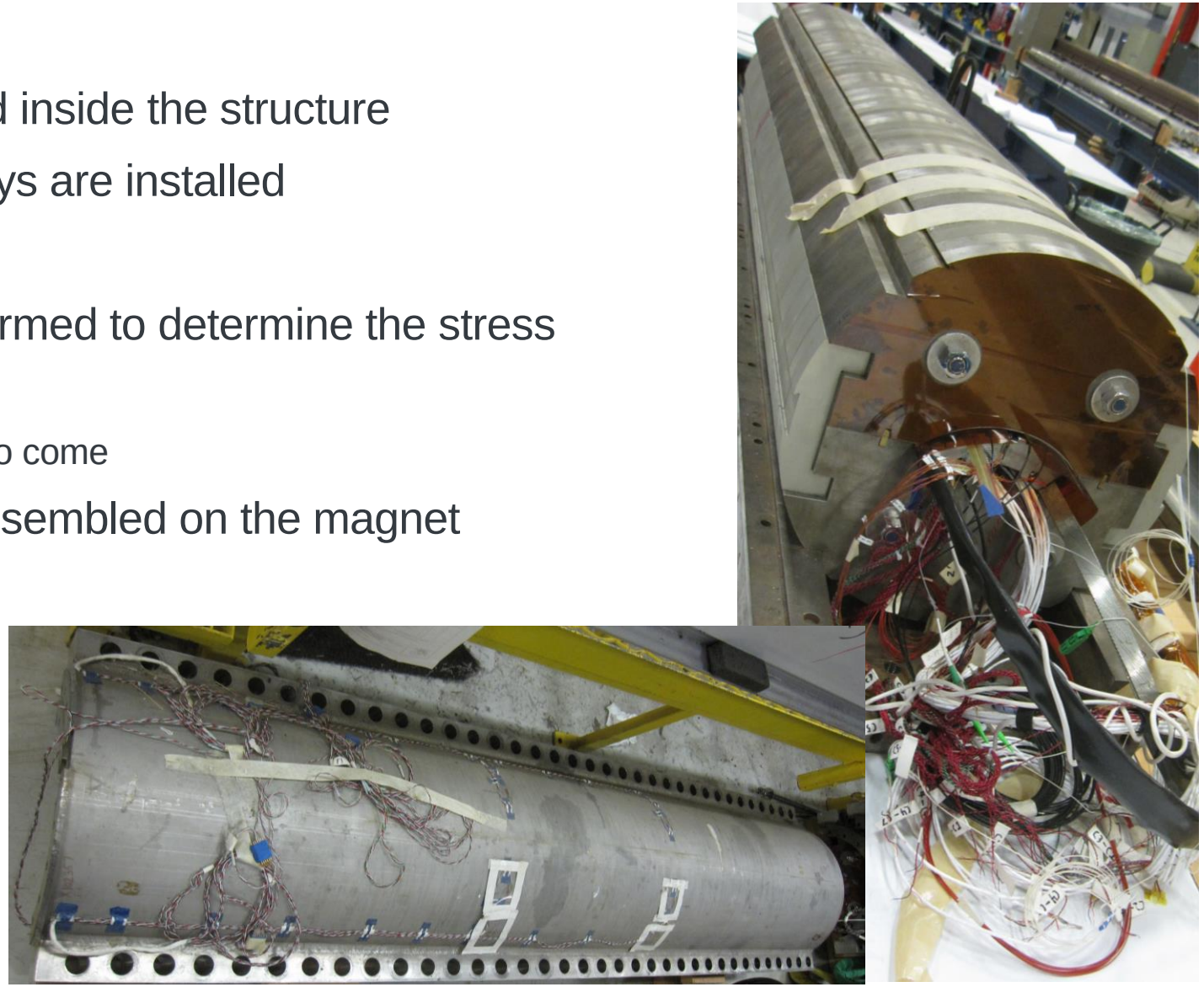


A DAQ module prototype

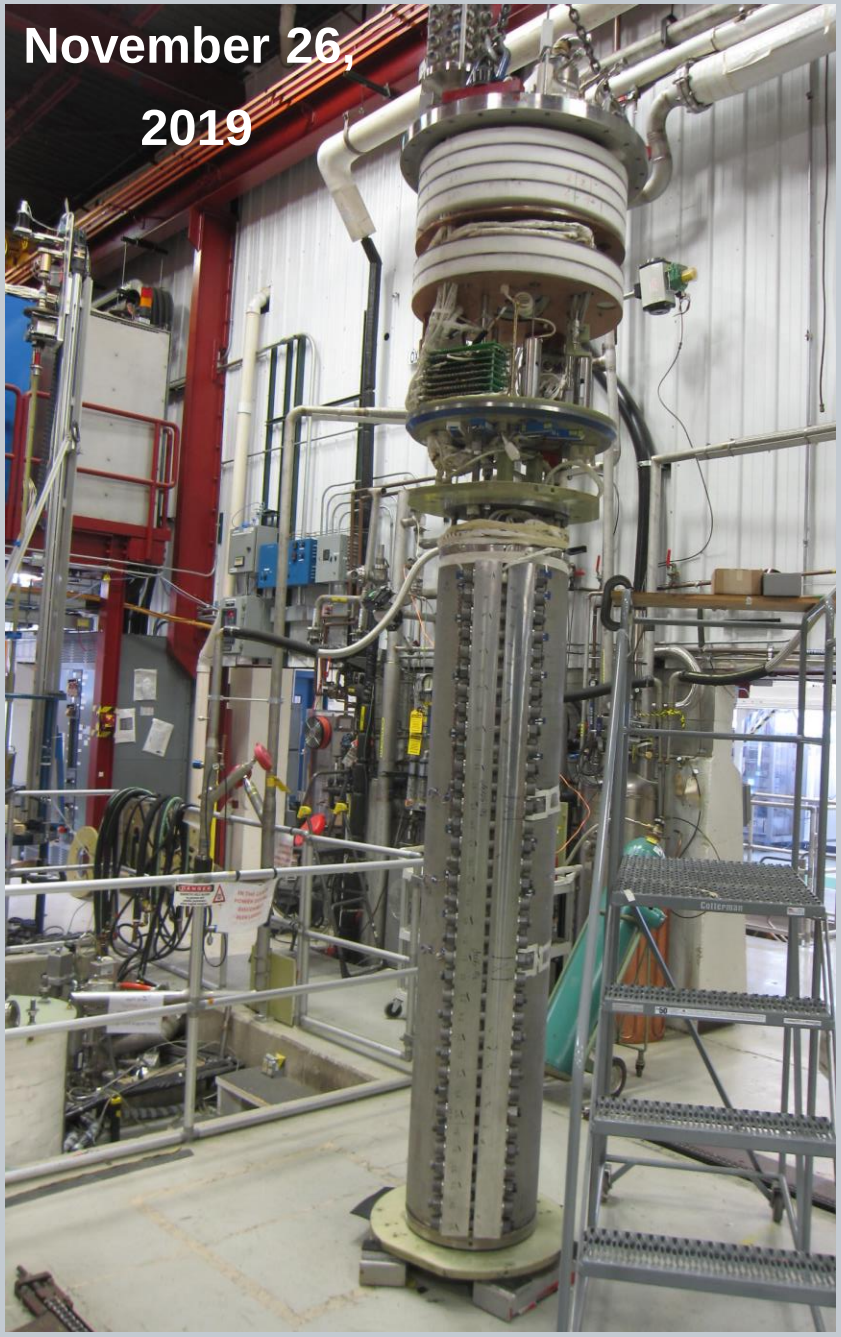
*M. Baldini, S. Krave, R. Bossert, S. Feher, T. Strauss and A. Vouris, "Application of Distributed Fiber Optic Strain Sensors to LMQXFA Cold Mass Welding," in IEEE Transactions on Applied Superconductivity, vol. 33, no. 5, pp. 1-5, Aug. 2023, Art no. 9000705, doi: 10.1109/TASC.2023.3258904.

# Status and plans

- The instrumented coil is placed inside the structure
- All laminations, clamps and keys are installed
- All shimming work is complete
- Multiple press tests were performed to determine the stress
  - on coil and structure
  - the final pre-stress setting is yet to come
- The bolted skin needs to be assembled on the magnet
  - Setting the final pre-stress
  - End-plates to be installed along with “bullet” strain gauges
- Electrical checkout before relocation to the test stand
- Preparations for testing within six months



Magnet structure and skin




MQXFSM2 next to the VMTF at FNAL

# Summary

"Mirror magnet experiment"

## Our "experiment" has a long list of goals

Controlled quench environment, current redistribution understanding, voltage development characterization, commissioning of various tools and analysis methods

## Our timing is getting stretched

Resources and priorities are still tough, but we are at the final stretch – skin placing on the magnet, final pre-stress setting

## Realistically, we plan to test in 2026

It is difficult to predict with certainty, but we expect that results by summer 2026 are an achievable target

# Acknowledgments

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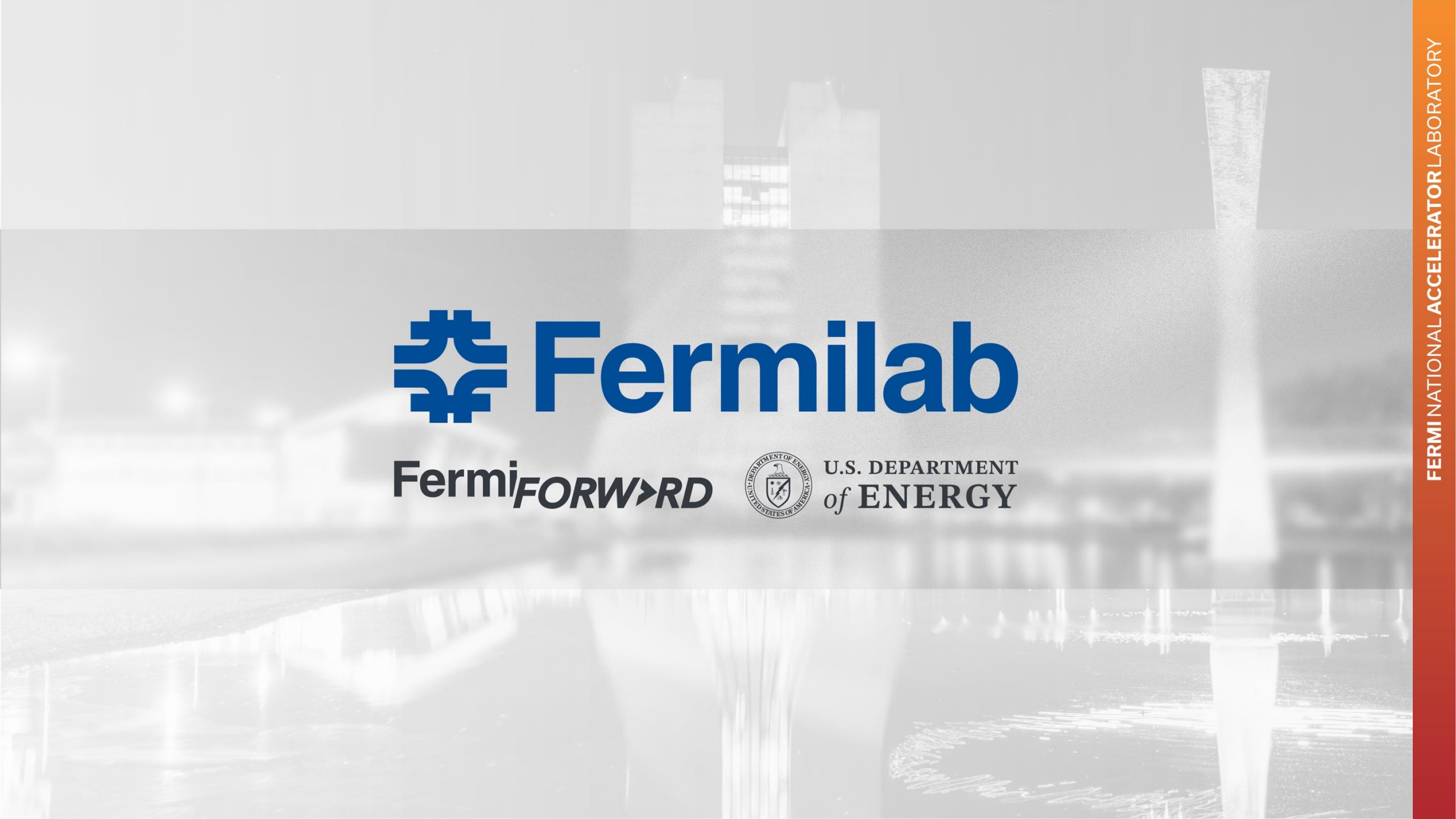
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