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R&D needs for "cold" electronics for superconducting magnets - Fermilab perspective

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Thanks to Roger Rabehl, Tony Vouris, Tom Cummings (FNAL)

Outline

- Superconducting magnet R&D goals in the context of data taking
- Data communication lines at a superconducting (accelerator) magnet test faculty
- Data taken, needs and limitations
- Sensor arrays are here to stay – more channels
- Data characteristics request : based on 21-st century architecture → "Cold" electronics
- "Cold" (cryo) electronics wish list
- Past and contemporary support by FNAL magnet systems
- What are we missing?

R&D goals (accelerator magnets)

U.S. MAGNET DEVELOPMENT PROGRAM

https://science.osti.gov/-/media/hep/pdf/Reports/2020/USMDP-2020-Plan-Update-web.pdf

Program goals

***Explore the performance limits** of Nb_3Sn accelerator magnets*, with a sharpened focus on minimizing the required operating margin and significantly reducing or eliminating training

Develop and demonstrate an HTS accelerator magnet with a self-field of 5 T or greater, compatible with operation in a hybrid HTS/LTS magnet for fields beyond 16 T

***Investigate fundamental aspects** of magnet design and technology* that can lead to substantial performance improvements and magnet cost reduction

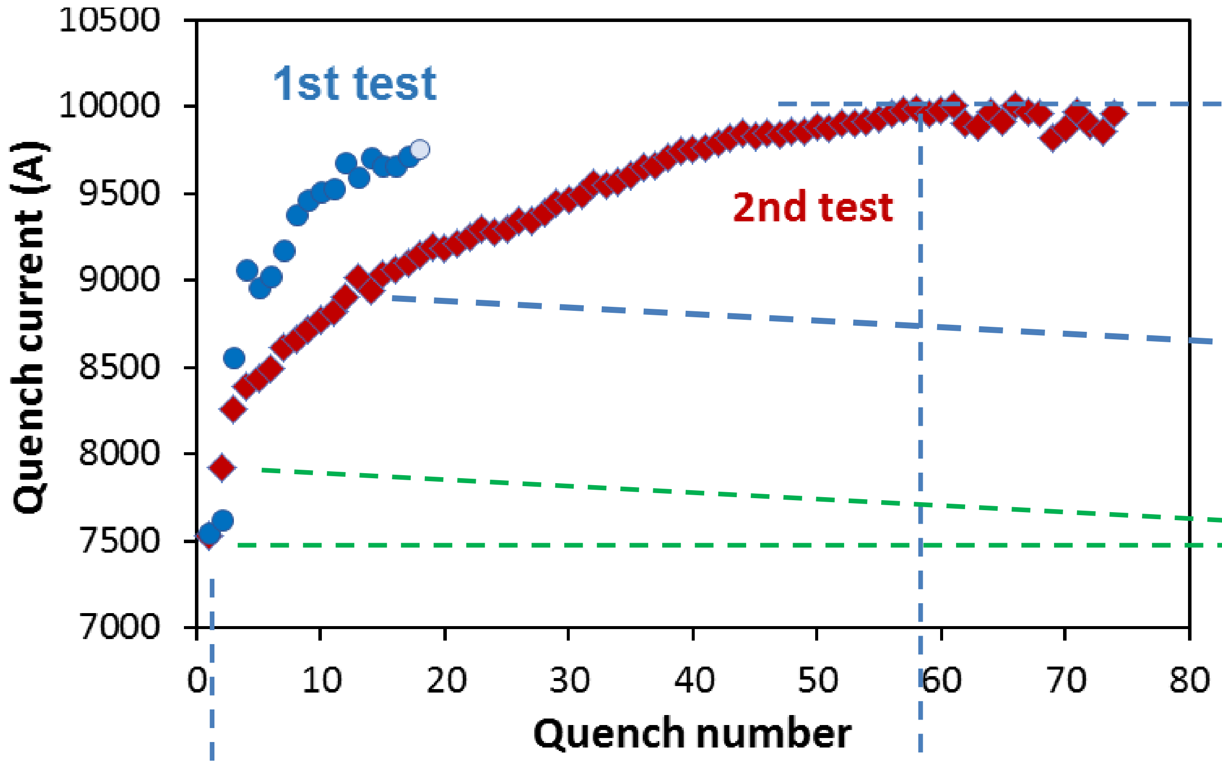
Pursue Nb_3Sn and HTS conductor R&D with clear targets to increase performance, understand present performance limits, and reduce the cost of accelerator magnets

We need to understand complex phenomena and that requires a multi-physics approach, with attention to finer spatial and temporal resolution than before.
Simulation tools are of great help, and given their improving quality they need too to be validated much more precisely than in past.

More data
More data sources
Better precision
Good synchronization

Superconducting magnet performance questions

Training curve of the 15 T magnet demonstrator (FNAL)



What drives the ultimate current (and field) level (often magnets can not reach their design levels)

What exactly is going on in any of those events?!

Why quenches start here and why magnets don't "remember" their training <u>sometimes</u>

Can we shorten this period (it is very expensive)

Can we predict/quantitively describe all/any of this?

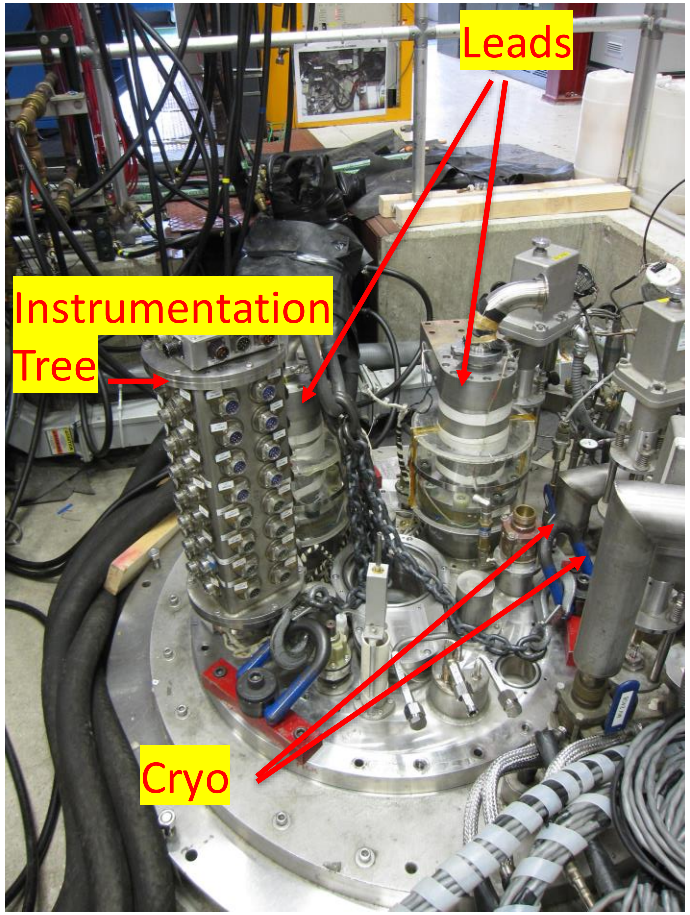
More data
More data sources
Better precision
Good synchronization

A. V. Zlobin et al., "Reassembly and Test of High-Field Nb3Sn Dipole Demonstrator MDPCT1," in IEEE Transactions on Applied Superconductivity, vol. 31, no. 5, pp. 1-6, Aug. 2021, Art no. 4000506, doi: 10.1109/TASC.2021.3057571.

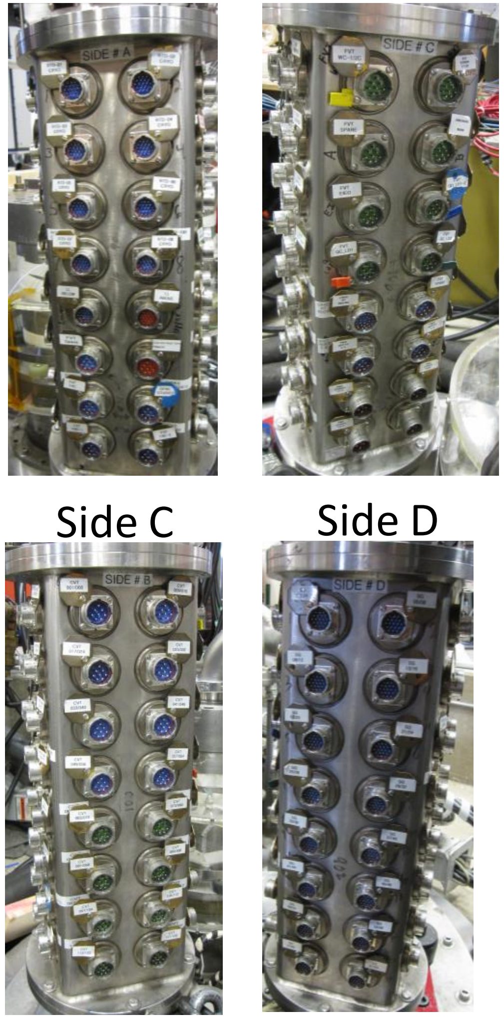
How does a typical “cold” testing facility get data

FNAL example

VMTF at FNAL



Instrumentation Tree



Side A: temperature and liquid level sensors, auxiliary CVT channels

Side B: Quench characterization (CVT) channels (including quench antenna)

Side C: Quench detection/ magnet protection and heater power/readout connectors

Side D: Strain gauge connectors

(various gauges/connectors; all are graded to sustain 1+ kV – pin-to-pin or to ground)

VMTF Facility limits

128 pins for quench characterization

~32 pins for magnet protection

64 + 8 strain gauge channels (including powering)

16 (4-wire) channels for protection heaters

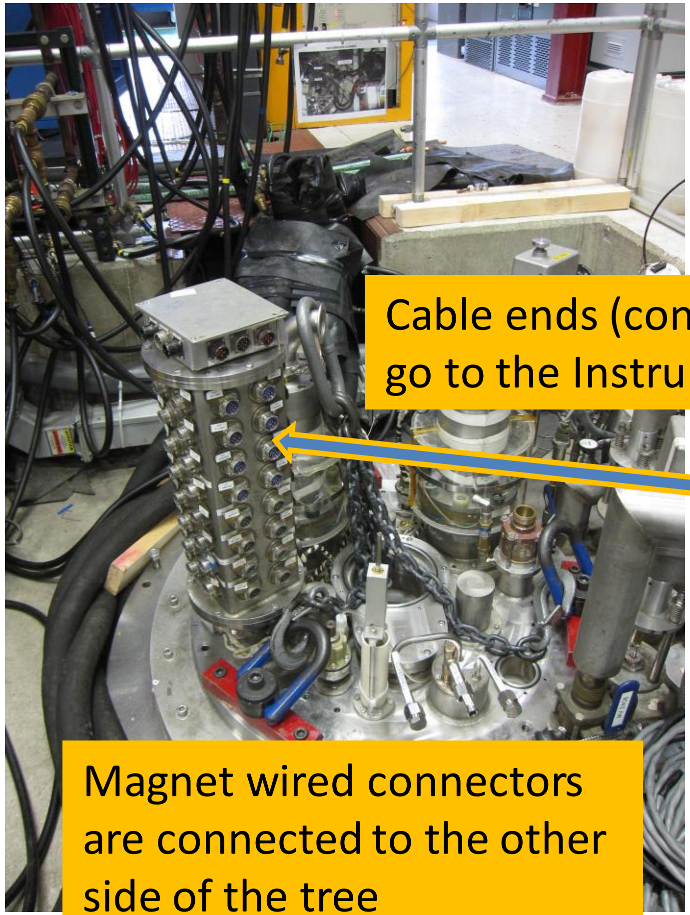
~ 32 pins for cryo-support sensors

~ 16 auxiliary pins

~ 500 pins (“wires”)

How does a typical “cold” testing facility get data (2)

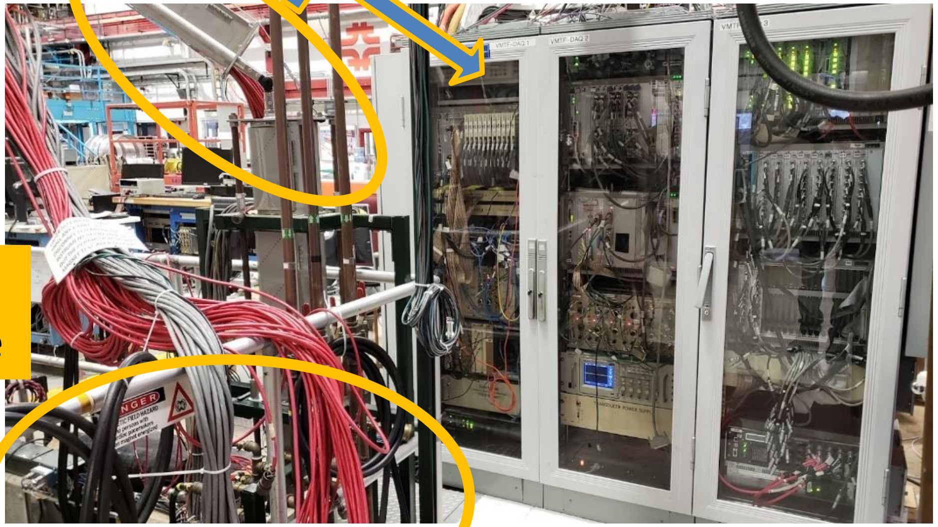
FNAL example



Cable ends (connectors) go to the Instrumentation tree

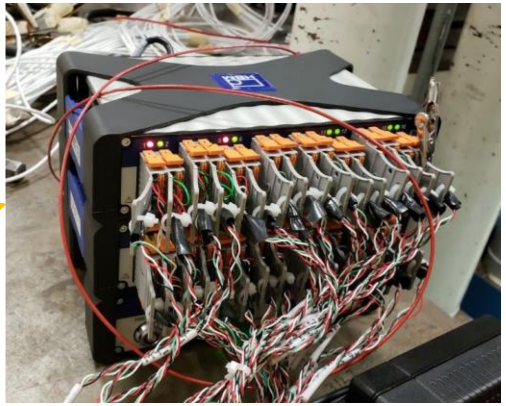
Magnet wired connectors are connected to the other side of the tree (below ground level)

The other cable ends go here (DAQ)

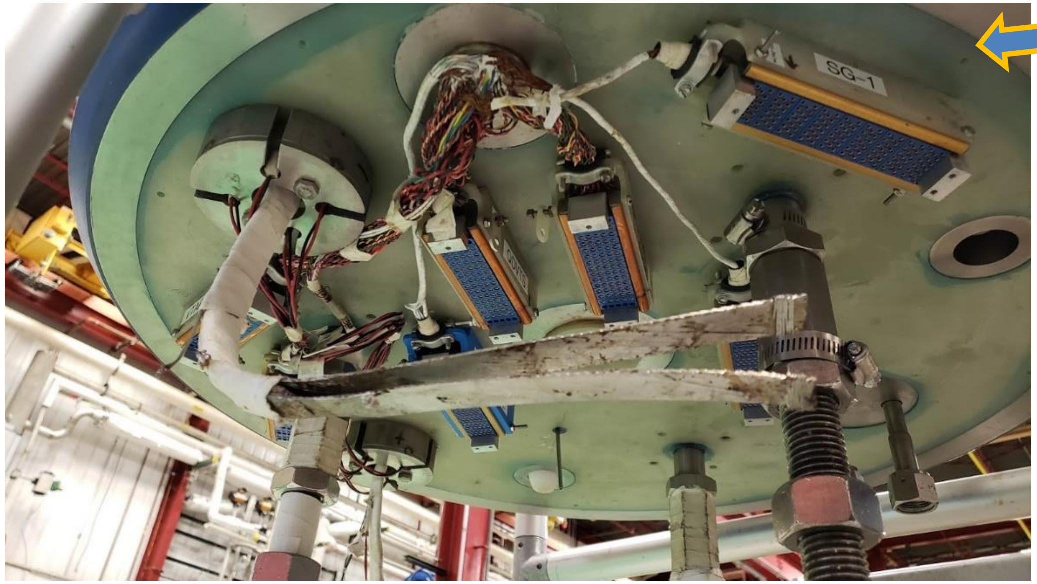


The whole electronics in the rack on the left is replaceable by the ~ 10”x10” device below.

Sometimes a stand-alone DAQ is used, still utilizing the Instrumentation tree



Below ground level



"Lambda plate"
(allows for < 2.1 K operation in LHe, typically < 1.9 K)

- Much more feed-throughs for wires risk to tilt the heat balance, there are practical limitations
- We will also run out of space with too many wires and connectors (nevermind the complexity and risk of dealing with multiple wire bunches and connections)

But the world ran "just fine" for tens of years that way, do we really need more data from magnets, how much more?

For production magnets (like LHC ones) we don't need more data. R&D test facilities are a whole different story…

“Cold” data

NOW

Channel	Count	Bit Depth	Frequency (kHz)	Channel Bandwidth (kbps)	Bandwidth (kbps)	Wires per channel	Total Wires
Strain, temp.	70	24	0.0003	0.007	0.5	4	280
Quench Ant	15	16	7	112	1680	2	30
vtap	100	16	7	112	11200	1	100
Acoustic	5	16	1000	16000	80000	2	10
Total Bandwidth					93000		
In Mbps					**93**		
with overhead					**200**		
Total Wires							**~450**

Mid-range high-speed internet

We may want to increase DAQ rate to ~ 10 kHz, at least for part of the channels

We definitely want to increase both number of channels (100s) and DAQ rate (~ 100 kHz)

We want to take data at 100 kHz

We can work with 100-1000 kHz rate, we may want to increase the number of channels

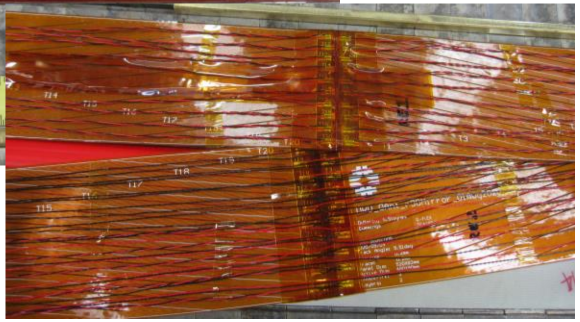
Other instrumentation types, potentially with multi-channels:
Hall-probes, fiber-optics, temperature sensors, …
Arrays could provide fine resolution multi-physics data.

It is easy to see that we take as much data as we can at the bandwidth we can afford.
Those limits are often impeding development of advanced diagnostics.
The biggest problem currently is the number of available channels (“wires”).

Multi-channel push

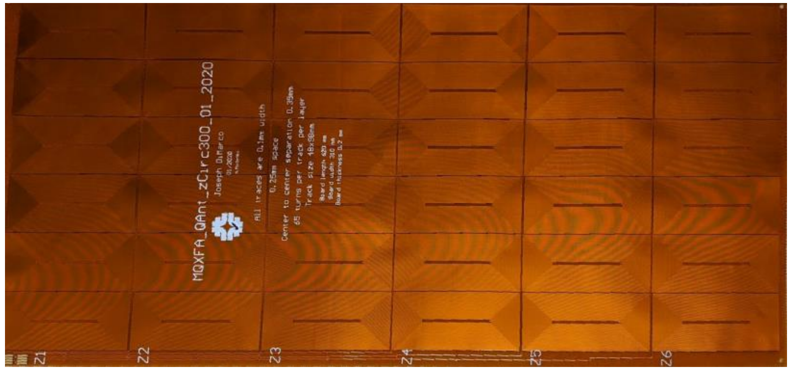
AUP quench antenna array for in-bore reading (warm)

Flexible PCB quench antennas (flex-QA) are a good **example** of array based high-rate instrumentation that puts much stronger demands on test stand support.



R&D quench antenna array "on coil" (cold)

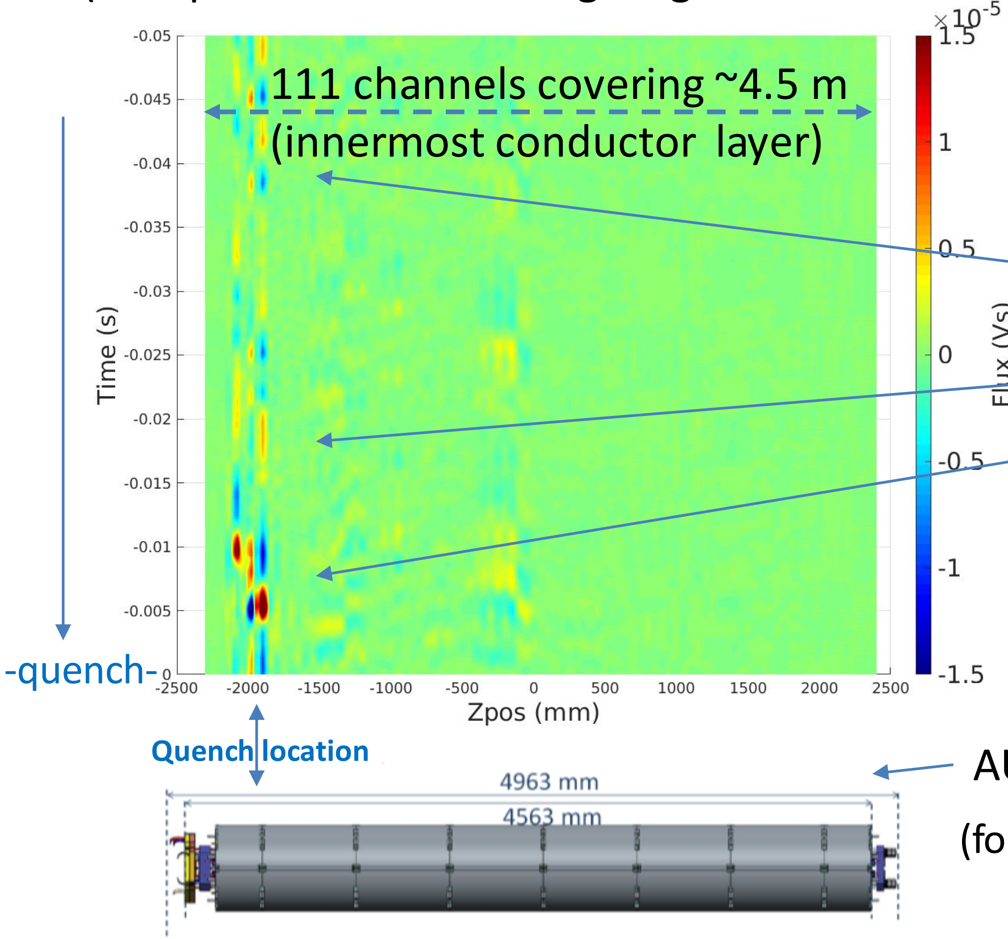
J. DiMarco et al., "A Full-Length Quench Antenna Array for MQXFA Production Series Quadrupole Magnet Testing," in IEEE Transactions on Applied Superconductivity, vol. 31, no. 5, pp. 1-5, Aug. 2021, Art no. 9500705, doi: 10.1109/TASC.2021.3068933.



Spatial resolution relates to the size of individual channels. Experiments show that even small flex-QA are also very sensitive; those QA likely can only read close-by coils. To cover all coil surfaces with good resolution a lot of channels are needed, ideally a proper signal processing can happen on-board.

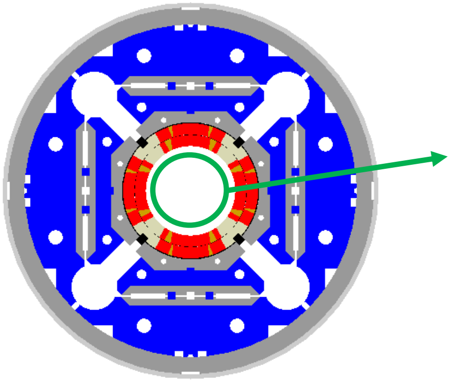
Multi-channel push (2)

Cumulative pre-quench flux vs time and axial location
(AUP pre-series 4.2 m long magnet tested at BNL)



AUP magnet

(for visualization)



This is a “warm” quench antenna (QA) array measurement. However, “warm” QA devices are only partially applicable (“surface” measurements).

Much better precision is needed and coverage of all relevant magnet areas is necessary in R&D.

This is part of comprehensive data we hope one day will help us paint the full picture of the actual pre-quench events

The QA only covers the innermost surface of the magnet (coils)

J. DiMarco et al., "A Full-Length Quench Antenna Array for MQXFA Production Series Quadrupole Magnet Testing," in IEEE Transactions on Applied Superconductivity, vol. 31, no. 5, pp. 1-5, Aug. 2021, Art no. 9500705, doi: 10.1109/TASC.2021.3068933.

H. Pan et al., "Mechanical Design Studies of the MQXF Long Model Quadrupole for the HiLumi LHC," in IEEE Transactions on Applied Superconductivity, vol. 27, no. 4, pp. 1-5, June 2017, Art no. 4004105, doi: 10.1109/TASC.2016.2642169.

Extended-data limits

Voltage taps: <u>100 channels x 16 bits x 100 kHz</u>

(no amplifiers necessary but channels need to be isolated due to risk of high voltages)

bits	depth
16	65,536
14	16,384
12	4,096

For quench characterization with no amplifiers:
±1 V range (we need negative readings for inductive response) and 16 bits gives ~30 μV resolution, ±5 V range is acceptable too (*can we regulate range without amplifiers?*).
12 bits and less at ±5 V range is detrimental for R&D purposes (will benefit from dynamic range options or amplifiers)

160 Mbps total (we need to read all channels)

Strain gauges: 70 channels x 24 bits x 10 kHz

The dynamic range can be squeezed a lot (bridge configurations) and it is not clear how useful sensors can be at high rate. Provisionally we can work with just *<u>10 channels x 16 bits and 10 kHz</u>* but this may get expanded.

1.6 Mbps total (limited number of channels of interest)

Extended-data limits (2)

Quench antennas: 200 channels x 16 bits x 100 kHz

(no amplifiers necessary)

±5 V range and 16 bits gives ~0.15 mV resolution,
May be able to work with 14 bits but not 12 bits without changing the range.

bits	depth
16	65,536
14	16,384
12	4,096

320 Mbps total (could get extended by a factor of two at least, easily)

It may be possible to multiplex (read "interesting" data only),
requires more data processing at "cold"; it is not given this works for us in all cases

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Acoustic sensors: 5 channels x 16 bits x 500 kHz

(no new electronics necessary but may use different means of transmission)

±5 V range and 16 bits gives ~0.15 mV resolution,
12 bits will still be acceptable. Developments requiring a large array of channels is a possibility (reducing data rate and bits per channel)

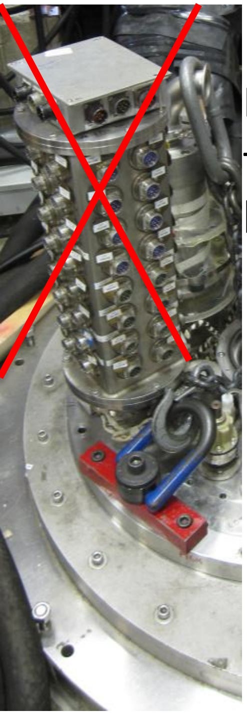
40 Mbps total (some possibility to extend by a factor of 10)

Temperature/Hall sensors: 100 channels x 16 bits x 1/100 kHz
(those are potential developments, other may arise)

Limits driven by Hall probes. Those are similar to and can be considered in OR with the Quench antenna.

Extended-data limits (3)

The **total data rate** comes to 530 Mbps and including possible extensions and provisional channels for future development **can be set at 1 Gbps**.



Ethernet or fiber-optics cables are applicable though their stable performance at cryo-temperatures should be assessed

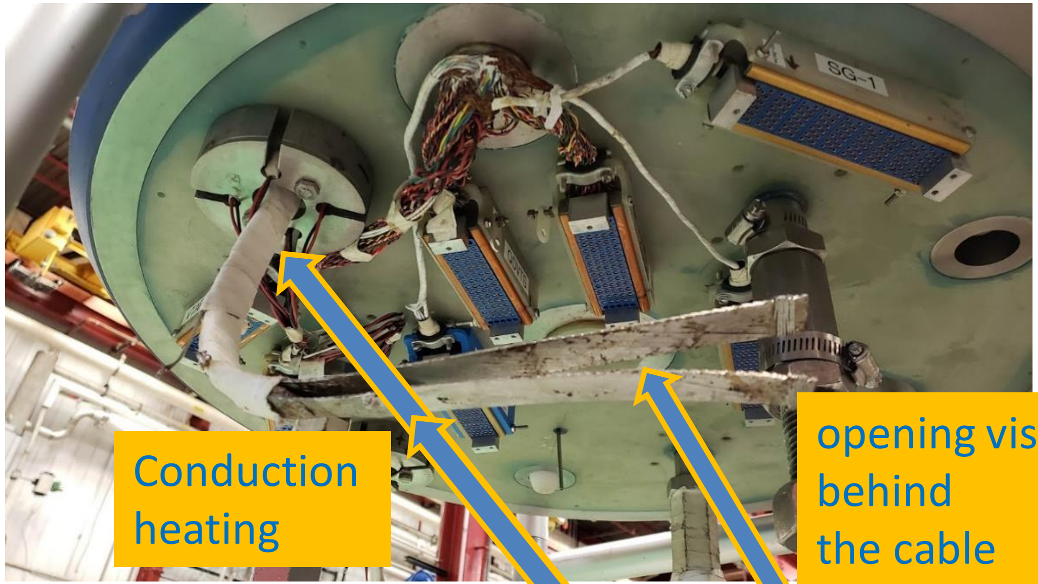
Ethernet Cables

Category	Max. Data Rate	Bandwidth	Max. Distance	Usage
Category 1	1 Mbps	0.4 MHz		Telephone and modem lines
Category 2	4 Mbps	4 MHz		LocalTalk & Telephone
Category 3	10 Mbps	16 MHz	100 m (328 ft.)	10BaseT Ethernet
Category 4	16 Mbps	20 MHz	100 m (328 ft.)	Token Ring
Category 5	100 Mbps	100 MHz	100 m (328 ft.)	100BaseT Ethernet
Category 5e	1 Gbps	100 MHz	100 m (328 ft.)	100BaseT Ethernet, residential homes
Category 6	1 Gbps	250 MHz	100 m (328 ft.) 10Gb at 37 m (121 ft.)	Gigabit Ethernet, commercial buildings
Category 6a	10 Gbps	500 MHz	100 m (328 ft.)	Gigabit Ethernet in data centers and commercial buildings
Category 7	10 Gbps	600 MHz	100 m (328 ft.)	10 Gbps Core Infrastructure
Category 7a	10 Gbps	1000 MHz	100 m (328 ft.) 40Gb at 50 m (164 ft.)	10 Gbps Core Infrastructure
Category 8	25 Gbps (Cat8.1) 40 Gbps (Cat8.2)	2000 MHz	30 m (98 ft.)	

Cable Type	Typical Gauge	Diameter (inches)
Cat8	22 AWG	0.0253
Cat6/Cat6a	23 AWG	0.0226
Cat5e	24 AWG	0.0201
Slim Cat6	28 AWG	0.0126
Ultra Slim Cat6	32 AWG	0.0080

https://www.tripplite.com/products/ethernet-cable-types

Heat load limitations



Conduction heating

opening visible behind the cable

- According to our engineers an unmodified Lambda-plate can handle 30 W of additional power below it (1.9 K operation)
- Operation without the warm bore tube (sealed) gives an additional margin of 6 W
- Existing cable feed-throughs
do not contribute substantially to the heat load

Heat load is dominated by bus work, warm bore tube and direct leaks between the two plate sides.

Thus, the upper limit for "cold" electronics is ~ 30-40 W.
We don't expect much higher limits in other test facilities of this type, may be lower.

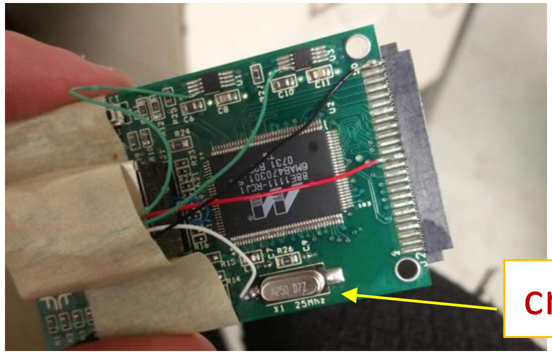
We could work with higher power dissipation (factor of two?) at 4.5 K but liquid usage efficiency suffers, and we have limited liquid flow anyway.

“Cold” electronics wish list

- At least 1 Gbps data rate
- At least 250 channels
- fully differential input(s)
- 250 kHz sampling per channel
- At least 16 bits in (-5 V, 5 V) signal range; preferably configurable
- another option is the use of “cold” amplifiers with at least gain of 10
- separately – development of isolation amplifiers for use at the above conditions
  - differential input protection of 500 V in working conditions
  - 2 kV channel-to-channel, and channel-to-ground isolation in working conditions
- developed electronics should use less than 100 mW of power per channel ← 300 channels at 30 W (to start with)
- the system should be able to start and operate in liquid helium

Contacts and early support

- Working with Marcos T. (LBNL) and Ryan R. (FNAL, Computing Divisions) who are main developers
- A Summer student (Kevin Riley) was helping a couple of years ago



crystal

- GEL Board was tested in **liquid nitrogen**
- Did not work with the crystal (clocking device)
- It worked without it and a CAPTAN board attached for testing of the board as an operating ethernet link

crystal removed

For this test, the voltage regulators were also removed, and leads were reattached to the output pads of the regulators

The goal of the test was to clarify which components of the GEL board could operate in cryo-environment

Continuing support

- Continuing cooperation with Marcos T. (LBNL) and Ryan R. (FNAL, Computing Divisions)
- Divya S. (FNAL, Computing division) is performing the latest round of testing

The project at FNAL Computing Division requires operation in liquid nitrogen/argon.
We benefit from partially aligned development goals.

- A 3-channel power supply,
- 1.5 V, 2.5 V, 4.7 V voltages are used for cryo-captan (including miniADC).
- <u>Ryan's talk covers the relevant details</u>
- Testing in liquid nitrogen only for now
- Once those prove to be working, we'll test in liquid helium (1.9 K and 4.5 K) **but** there is no plan of action in case they do not work in liquid helium (no resources for development)

SBIR/STTRs?

- While there is some collaboration with industry, so far, we did not provide to DOE a proper description/request for development among the DOE annual SBIR/STTR topics (for acc. magnets)
- We are working on proposal to DOE to include a sub-topic for accelerator magnets

We are very much inclined in supporting industry development of "cold" electronics.

Small Business Innovation Research (SBIR) and Small Business Technology Transfer (STTR) Program

SUPERCONDUCTOR TECHNOLOGIES FOR PARTICLE ACCELERATORS

Draft-proposal for a dedicated sub-topic (may change before sending):

Grant applications are sought to develop electronics working at liquid helium temperatures (a.k.a. "cold" electronics). The main issue to resolve is optimizing the space required for feed-through channels being brought from liquid helium to room temperature by digitizing the signals and transmitting them through large bandwidth connections. The main target parameters are 1 Gbps data rate, at least 14 (better 16) bits per channel and sampling rates above 200 kHz. Use of amplifiers is recommended. The power consumption should be less than 100 mW per channel and the system should be able to start and operate in super-fluid liquid helium.

Summary

- Significant superconducting magnet R&D is needed to make good progress on performance
- Up to date research questions and techniques require much larger data and channel footprint than available
- We are still relying on direct signal transfer from “cold” to “warm” environment
- Our immediate needs could be met by the ability to transfer additional few hundreds of channels with total data rate of 1 Gbps but those could easily be exceeded
- “Cold” electronics with “modest” requirements can serve this purpose and there is no practical alternative
- While FNAL is assisting in this research we could not afford to invest in it significantly
- We are open to partnerships and supporting industry and are trying to promote the importance of this field of development

Spare