U.S. MAGNET DEVELOPMENT PROGRAM

Training Reduction studies (a personal retrospective view toward the future)

MDP Meeting

May 2, 2024

Stoyan Stoynev[1]

US Magnet Development Program

[1]Fermi National Accelerator Laboratory

Guidance for talks (George/Soren)

"…**planning these talks, please consider the following points:**

Summarizing the status of the R&D topics, the summary can be presented by several people.

a. **Discussing issues encountered** over the last year and **proposed solutions** (lessons learned).

b. Discussing **current or upcoming milestones** (next 6-8 months) – **can they be met**? If not, what are the **obstacles to progress**?

c. Identifying near and mid-term conductor needs to provide guidance to the CPRD group.

Proposing one or more additional technical talks focusing on specific R&D crucial to delivering on the roadmap. Each area should plan these with consideration of time to allow sufficient discussion time. The total time allotted should not exceed 2 hours and 30 minutes, including discussions.

Allocating time for discussion (at least 30 minutes):

a. **Identifying R&D issues**.

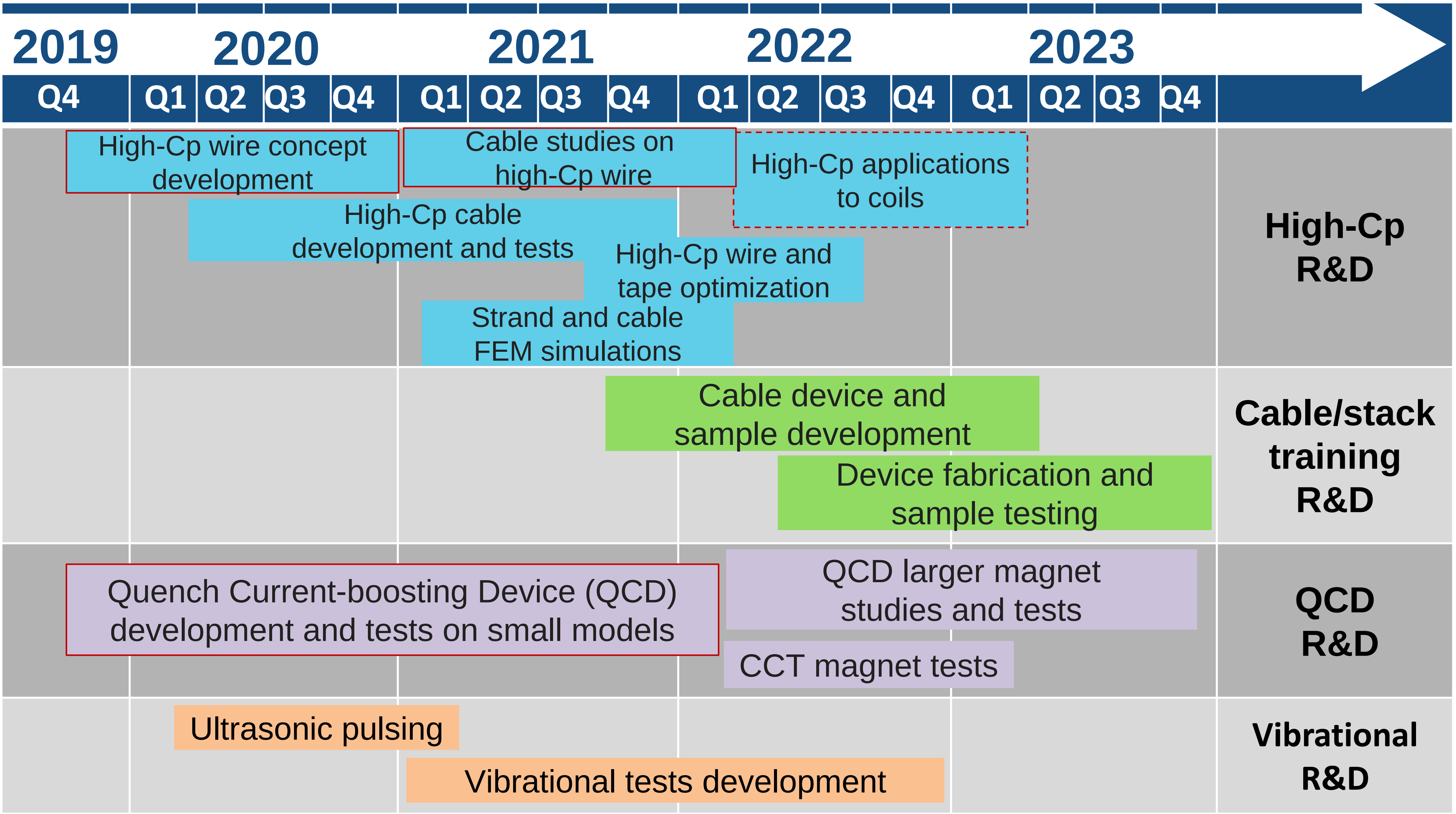
b. **Discussing challenges**, if any, in meeting the milestones.

c. Addressing conductor needs for the next two years."

This is what I'll be talking about:

- **Summarizing the status**
- **Obstacles to progress**
- **Discussing issues encountered**
- **Proposed solutions**
- **Identifying R&D issues**
- **Discussing challenges**

Training reduction topics (as presented in 2020)

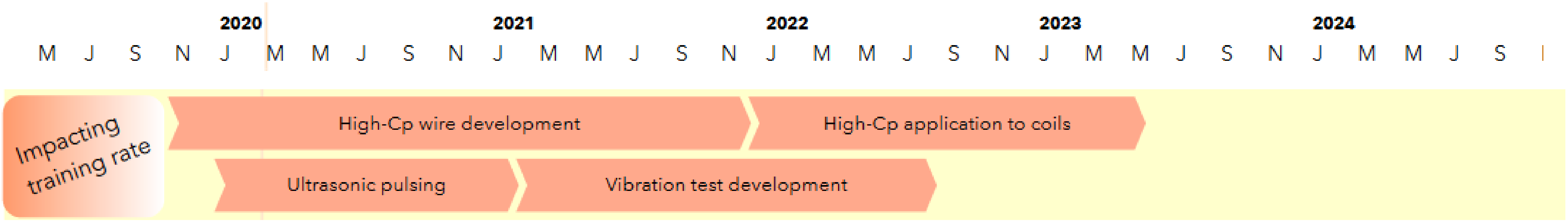


My talk will touch upon those

In red border lines – independent funding

Official training reduction roadmap

Roadmap as in the official document:



https://science.osti.gov/hep/Community-Resources/Reports
MDP roadmap there

(Training Reduction) Milestones in MDP

Training Reduction Milestones

Milestone #	Description	Target		Updated Target	Requestor	Comments
AIIe-M1	Commissioning of QCD		Done		S. Stoynev	
AIIe-M2	First Ultrasound based test		Obsolete		S. Stoynev	It should be retired (removed), it is not a viable option anymore
AIIe-M3	First high-Cp cable fabrication with high-Cp tape	n/a	In progress	n/a	E. Barzi	Target dates cannot be provided without allocated resources
AIIe-M4	First magnet test with QCD		Done		S. Stoynev	
AIIe-M5	Results from High-Cp cable studies	n/a	In progress	n/a	E. Barzi	Target dates cannot be provided without allocated resources
AIIe-M6	Optimized strand and cable FEM simulations	n/a	In progress	n/a	E. Barzi	Target dates cannot be provided without allocated resources
AIIe-M7	First CCT test with QCD	Apr-24	Obsolete		S. Stoynev	Can not be done due to MIITs limitations (but the CCT test itself is progressing)
AIIe-M8	High-Cp wire and tape optimized versions		Obsolete		S. Stoynev	We have split this milestone (in 2022)
AIIe-M8a	High-Cp wire optimized versions	n/a	In progress	May-24	X. Xu	
AIIe-M8b	High-Cp tape optimized versions	n/a	Not started	n/a	E. Barzi	No allocated resources
AIIe-M9	Fabrication of first coil with High-Cp conductor	n/a	Not started	n/a	X. Xu	Schedule is hard to predict as it involves many efforts from collaborators, e.g., cabling, coil fabrication, etc.
AIIe-M10	Design of a dedicated device/technique using vibrational methods	Apr-25	In progress	Apr-25	S. Stoynev	Activities progressing slowly due to level of priorities (Mike K. + students)
AIIe-M11	Design of a “cable/stack” testing device and samples		Obsolete		S. Stoynev	See the new Milestone
AIIe-M12	QCD preparations and test on a large magnet		Obsolete		S. Stoynev	It should be retired (removed), it is not a realistic option anymore
AIIe-M13	Fabrication of a “cable/stack” testing device		Obsolete		S. Stoynev	See the new Milestone
AIIe-M13a	Design and fabrication of a “cable/stack” testing device	Sep-25	Not started	Apr-26	S. Stoynev	No concrete agreements for support yet (the milestone will move next time if status remains)

*Status

- Done
- In progress
- Not started
- Obsolete

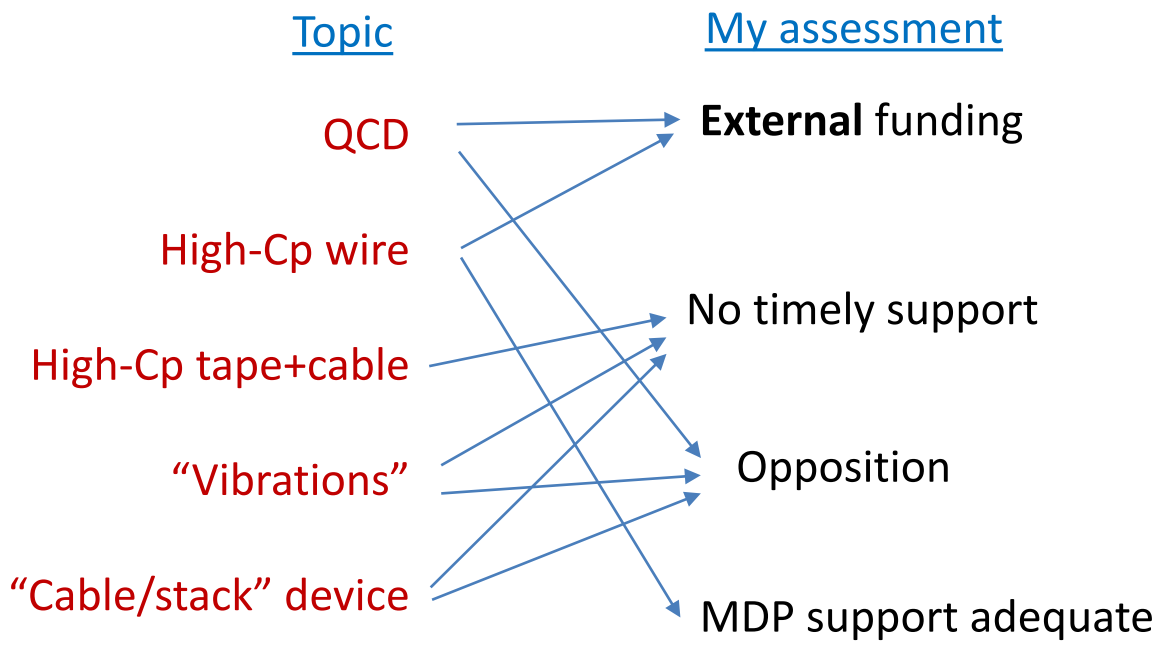
https://science.osti.gov/hep/Community-Resources/Reports

MDP roadmap there

Topics' Support

An attempt to characterize main trends in support, or lack thereof, among topics

Milestone #	Description
AIIIe-M1	Commissioning of QCD
AIIIe-M2	First Ultrasound based test
AIIIe-M3	First high-Cp cable fabrication
AIIIe-M4	First magnet test with QCD
AIIIe-M5	Results from High-Cp cable studies
AIIIe-M6	Optimized strand and cable FEM simulations
AIIIe-M7	First CCT test with QCD
AIIIe-M8	High-Cp wire and tape optimized versions
AIIIe-M8a	High-Cp wire optimized versions
AIIIe-M8b	High-Cp tape optimized versions
AIIIe-M9	Fabrication of first coil with High-Cp conductor
AIIIe-M10	Design of a dedicated device/technique using vibrational methods
AIIIe-M11	Design of a "cable/stack" testing device and samples
AIIIe-M12	QCD preparations and test on a large magnet
AIIIe-M13	Fabrication of a "cable/stack" testing device
AIIIe-M13a	Design and fabrication of a "cable/stack" testing device



"Support" is not the same as "funding", it is more inclusive

R&D Support within "Training Reduction"

Each one of the four benefactors can, **"independently"** , make a given R&D topic (under MDP) progress:

A healthy program relies mostly on those

- **General** MDP community support
  something recognized by "all" as high priority (or considered as such by stakeholders)
- Strong **local** support
  "locality" depends on circumstances, but it involves "MDP funding"

The Training Reduction progress relies mostly on those (so far)

- **External** ("non-MDP") support
  including work against odds
- **Synergetic** support
  including "by chance" findings

The context here is "independent" but, certainly, any of those entities can work in concert
(like finding external funding even if another source is available; or having synergetic support while the topic is widely backed by MDP)

I'll call them "the four pillars", **"General", "Local, "External", "Synergetic"**
they work best together

US "training" studies outside "Training Reduction"

There are activities in the USA not among milestones in "Training Reduction" related to the "Training" topic

- Samples/magnets with TELENE impregnation (FNAL, Emanuela et al.) **"External"/ "Synergetic"**
- Development of training "samples" (FNAL, Sasha et al.) **"External"/"Synergetic"**
- Magnets with wax impregnation (LBNL)

I am probably missing more but those are what I am aware of

Just acknowledging such efforts are on going.
It is up to researchers to decide about the association of their efforts and formal goals.

(I mentioned those in the status report from January too)

Reflections of Past

High Field Magnet R&D Task Force Report

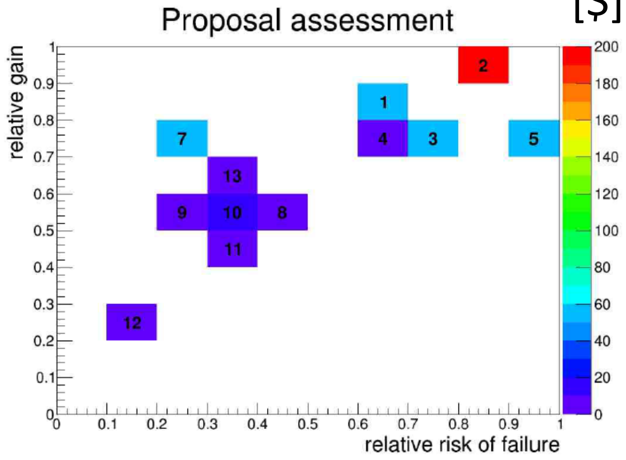
(FNAL internal, 2017-2018)

It had limited contributors by design (Lab mandated) and many people got omitted and disagreed with the set up;
the report was supposed to become public

WG5 - Understanding of Training and Improved Instrumentation

I did coordinate this one
(and it is true that I did not work on magnets before 2015)

This (WG) report had no effect on future policies at our Department/Division, as far as I can tell.



(FNAL internal document, 2017-2018)

Summary of proposals

The proposals discussed are as follows:

1. Cable stack → Still in MDP milestones, Snowmass contribution
2. Wire → magnet training program → Let's talk about it at the end
3. Capacitor training (Capacitor discharges through a magnet) → **QCD (LDRD, completed)**
4. Ultrasound (US) training (Mechanical "discharges" through a magnet) → Still in MDP milestones (evolved to "vibrations")
5. Insert pulse training (Magnetic "discharges" through a magnet) → never came to that yet
6. (provisional)
7. Acoustics → The point was to introduce acoustics as a standard method and cover all ramp data at FNAL
8. SG/accelerometers (fast) → We failed once but it should work
9. QA on a trace → **flex-QA arrays/grid (LDRD, completed)**
10. SC grid (on a trace!) → never came to that yet
11. Second sound → never came to that yet
12. Parallel SC wire → never came to that (this or similar was done in past at FNAL and elsewhere)
13. Multispot heater studies → Still in MDP milestones

Progress can also quench – a case "study"

- It has been shown that quench "over-current" (CLIQ, QCD) affects coil/magnet training
- With presently available devices we very likely could train LHC magnets (they train in "strings" of ~ 154 magnets)

https://lss.fnal.gov/archive/2015/conf/fermilab-conf-15-635-td.pdf

One CLIQ unit is ~ 100 k$, one needs ~ 150 of them : 15 M$
Average LHC energy consumption per year is 600 GWh which is at least 60 M$
LHC magnets retraining takes ~ 9 months and includes much more than energy consumption;

https://home.web.cern.ch/resources/faqs/facts-and-figures-about-lhc
https://home.cern/news/news/accelerators/how-train-your-magnets

- It is highly beneficial to have devices helping with training (if nothing else is)

<u>If you accept the above,</u>

- **Why weren't capacitor-discharging devices like the above developed earlier?**
  (early indications of effects were claimed in 1980s but this is only a secondary argument)
- *What is the most distant time in past when devices like those could had been built?*
- *Why weren't they built?*

Development begets development

According to power supply experts (who built QCD) similar devices could had been built as early as 1970s (if not earlier)

If we would had benefited from CLIQ-like devices and we could had them built in past, why hadn't we?

Because **none of the pillars** was in support ⇨ **"General", "Local, "External", "Synergetic"**

- **General** community support
  something recognized by all as high priority
  (or considered as such by stakeholders)

- Strong **local** support
  "locality" depends on circumstances

- **External** support
  including work against odds

- **Synergetic** support
  including "by chance" findings

▪ There was no ENGINEERING need of this technology at the time, and "we" didn't care about the SCIENTIFIC knowledge from it

▪ Moreover, the only reason to have the technology now, for the stated purpose at least, is due to **"Synergetic"**; and to have a bit more understanding about it – due to **"External"**

Progress occurs when there are **conditions** for progress.
Better the conditions, better the (chance of) progress.
Conditions are managed by people.

“Scientific” vs “Engineering” targets

US Magnet Development Program (MDP) Goals:

GOAL 1:

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

GOAL 2:

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

GOAL 3:

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

GOAL 4:

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

Technology is the application of scientific knowledge to the practical aims of human life /Britannica/

“Scientific inquiry begins with a question and proceeds to generate and test hypotheses until the question is answered. In contrast, engineering design begins with a problem and proceeds to generate and test solutions until a preferred solution or solutions are reached. ***Whereas science seeks to understand, engineering seeks to meet people's needs****.”*

National Assessment Governing Board

https://www.nagb.gov/naep-subject-areas/technology-and-engineering-literacy/framework-archive/2014-technology-framework/toc/ch_2/design/design2.html

- I would argue that none of the MDP goals is explicitly about gaining scientific knowledge (this does not imply nobody is trying to acquire it)

  Like “reducing or eliminating training” vs “understanding of training”

- In my opinion, the balance between engineering development and scientific development is not right in MDP

  For example, the question “What is the direct practical benefit of doing the research X?” is tilting the balance in the wrong direction

I believe the present situation was “always” the case for superconducting accelerator magnets and if it worked in past then it must be fine now. **Except, LHC never reached the projected 14 TeV energy (due to dipole magnet training), 11-T dipoles will never be part of HL-LHC, and we are still extremely happy every time when a brand-new HL-LHC Nb_3Sn quadrupole magnet reaches ~75% SSL, not all of them made it** (we don’t go further than ~75% SSL, and we stay below most of the time).

Magnet Training was being addressed since ~ 1960s

A major factor in the design of large superconducting magnets is the problem of premature quenching, notably the 'training' effect, associated with the use of epoxy resin impregnants.

This paper draws attention to the existence of a simple but neglected solution to this problem. A review is given of a series of tests carried out in 1968–71 which showed that such effects were considerably reduced in the case of solenoid and quadrupole coils impregnated with wax or oil, allowing currents at least 85–90% of the critical value to be achieved consistently and reliably. The tests included a full scale prototype quadrupole (9 cm bore, 40 kG maximum field).

A discussion of the mechanical and thermal properties of such coils indicates no reason to doubt their long term reliability, and the adoption of this solution for operational magnets is recommended.

A solution to the 'training' problem in superconducting magnets

P. F. Smith and B. Colyer

Cryogenics

Volume 15, Issue 4, April 1975, Pages 201-207

We conclude that wax impregnation represents a simple and satisfactory technique for the contruction of high performance dc dipoles and quadrupoles and is free from the risk of the serious training effects often observed in resin-impregnated coils.

Understanding training in superconducting accelerator magnets using acoustic emission diagnostics

Maxim Marchevsky

It can be argued that training is such a hard problem to solve because our means of studying its underlying physics remain very limited. Also, there are significant unknown factors complicating a meaningful

arXiv:2203.08871 [physics.acc-ph] (2022)

Putting things in perspective:

Controlled and sustained nuclear fusion is a hard **engineering** problem being addressed for about 70 years now. "Training" is over 50 years old.

Do we think it is on par with nuclear fusion?

I don't think training is a hard **scientific** problem, but I think it is inadequately addressed (for 50 years).

"Asking the right question is half the answer" (quote attributed to many people)

There is nothing special about the "training" problem

The Process of Solving Complex Problems

Andreas Fischer, Samuel Greiff, and Joachim Funke[1]

Fischer, Andreas & Greiff, Samuel & Funke, Joachim. (2012). The Process of Solving Complex Problems. Journal of Problem Solving. 4. 19-42. 10.7771/1932-6246.1118.

https://docs.lib.purdue.edu/cgi/viewcontent.cgi?article=1118&context=jps

Systematic strategy selection on the solution process

(1) information generation (due to the initial intransparency of the situation), (2) information reduction (due to the overcharging complexity of the problem's structure), (3) model building (due to the interconnectedness of the variables), (4) dynamic decision making (due to the eigendynamics* of the system), and (5) evaluation (due to many, interfering and/or ill-defined goals).

I would argue #2 is the key for us

Astonishingly, we still regularly fail on #1 too!

* "Eigendynamic effects are defined as a connection of an output variable with itself, reflecting changes of the variable over time without any actions taken by the participant" (Computers & Education Volume 189, November 2022, Art. # 104579)

#2: Information reduction: from "complex" to "simpler"

I would also argue that the problem to solve is beyond training : quench behavior/characteristics (training is a subset).

- Data so far suggest that SC "magnets" don't train, instead **SC coils in those magnets train independently**
  - This is a long topic with, possibly, caveats
  - Let's narrow this to Nb_3Sn cos-theta coils
- Often, though not always, training quenches are in the "same" location/s (as far as we can tell)

  Is there a viable mechanism where a quench in one spot affects key quenching characteristics later in another spot?
- It is reasonable to start with the assumption that quenches are "local" and are not affected by long-distance effects
- That is, investigating "local" quenches might be quite enough to get understanding of all quenches
- A "local" quench (sequence) is constrained by its local conditions
- Emulating a "local" quench (sequence) requires emulating local conditions
  - Literary, a small sample reproducing those conditions (current, field, temperature, force/stress)

Supposedly, it is simple, reproducible, cheap, we can make many and test quickly

Development “logistics”

- How to advance on magnet training and performance without “silver bullets”
  - for studies, **reproducibility** is more important than peak achievements
  - nothing beats **statistics**, without enough “equivalent” tests we are guessing
  - … and **time** is another big factor for R&D – delays/wait can ruin it
  - **simplicity** is crucial in many cases, as is **cost**
  - without a consistently executed program… well, history repeating

(“simple solutions to a complicated problem”:
Quench over-current
Materials “absorbing”/avoiding disturbance effects
(high-Cp, TELENE, wax, …) …

I’ll call them the “five make-or-break beams” : “Reproducibility”, “Statistics”, “Timing”, “Simplicity”, “Cost”

- How to advance on training and performance with unclear support commitments? What is reasonable?

Superconducting magnets of any kind are expensive, some more than others; even in R&D “series” the magnets are never the same (limited statistics) and the potential for good reproducibility is questionable. “Sub-scale” CCTs (evolved from models called “sub-scales” themselves) may be addressing many of those issues but I couldn’t call it a universal approach and they are still not “cheap” or “fast”, nor they are simple objects.

It took external influence for “everyone” in MDP to (suddenly) **accept and even embrace the notion that non-magnet “samples” can address many of the R&D issues; “samples” like the “BOX” experiment/setup.**

Sub-samples (non-magnets)

BOX: an efficient benchmark facility for the study and mitigation of interface-induced training in accelerator type high-field superconducting magnets

To cite this article: Michael Daly *et al* 2021 *Supercond. Sci. Technol.* **34** 115008

"BOX" – **"Local"** for developers, so far we are "observers"

- *What is the most distant time in past when devices like those could had been built?*
- *Why weren't they built?*

"General", "Local, "External", "Synergetic"

"BOX" is a step in the right direction but is not the full answer.

(from the developers)

process due to the smaller size of the BOX samples. In order to further reproduce high-field magnet behaviour, it may be feasible to wind two cables in parallel in one channel owed to the flexibility of the solenoid to supply up to 50 kA to two cables. This method could double the forces pulling the cables out of the channel. Furthermore, there is room for alterations to the BOX design by adding spot heaters to trigger quenches and to promote additional stress conditions by implementing *in situ* compressive stresses on the broad face of the cable during powering as is already performed at the facility [32]. Non-

Thinking outside the "box"?

Do we, in MDP, in 2024, agree with the authors' assessments made in 2021 (**"Timing"?**) that reproducing magnet behavior in samples in external magnetic field (original BOX) and "promoting additional stress conditions" (in authors' Discussions) is a good way to follow and it is worth supporting?

This is not a rhetorical question

Emulating local magnet conditions

2017/2018 1. **Cable stack** → Still in MDP milestones, Snowmass contribution

AIIIe-M13a	Design and fabrication of a "cable/stack" testing device	Sep-25	Not started	Apr-26
			S. Stoynev	No concrete agreements for support yet (the milestone will move next time if status remains)

(Reminder)

A device to create "tunable" local conditions (current, magnetic field, stress, temperature) for a "sample" (cable, cable stack, "interface", etc.)

Test samples and infrastructure for accelerator magnet developments

Stoyan Stoynev[1]

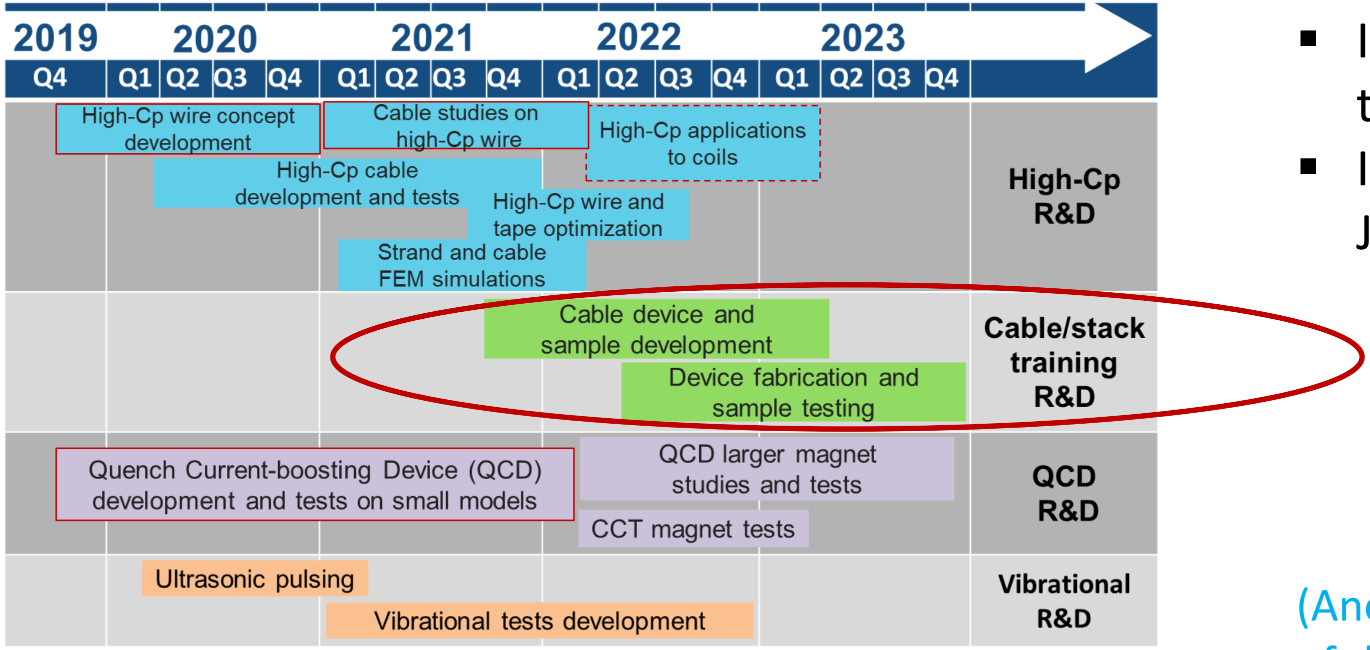
Comments:	contribution to Snowmass 2021 (AF)
Subjects:	**Accelerator Physics (physics.acc-ph)**
Cite as:	arXiv:2203.07274 **[physics.acc-ph]**

The "four pillars" : **"General", "Local, "External", "Synergetic"**

The "five beams" : "Reproducibility", "Statistics", "Timing", "Simplicity", "Cost"

Reminder:
The more of those are present better the chances of success

The cable/stack testing



- It has been in the MDP "plans" and milestones from the beginning of this kind of planning
- I used the "official" MDP form to "propose" it in January 2020 and in August 2020

The U.S. Magnet Development Program R&D Proposal
(Not more than 3 pages total)

Date:

Title: Stack and cable test stand in pressure and magnetic fields
Principal Investigator (institution): Stoyan Stoynev (Fermilab)
Co-Investigators (with institutions): ...

(Another proposal in that January – the initial version of the "mirror" magnet test , including spot heater array – we **may** manage to assemble the magnet with existing parts and do the test this year, 2024)

AIIIe-M13a	Design and fabrication of a "cable/stack" testing device	Sep-25	Not started	Apr-26
	S. Stoynev	No concrete agreements for support yet (the milestone will move next time if status remains)		

"General", "Local, "External", "Synergetic" -> Status in 2024 = "Failing", "Failing", "Failing", "Failing"

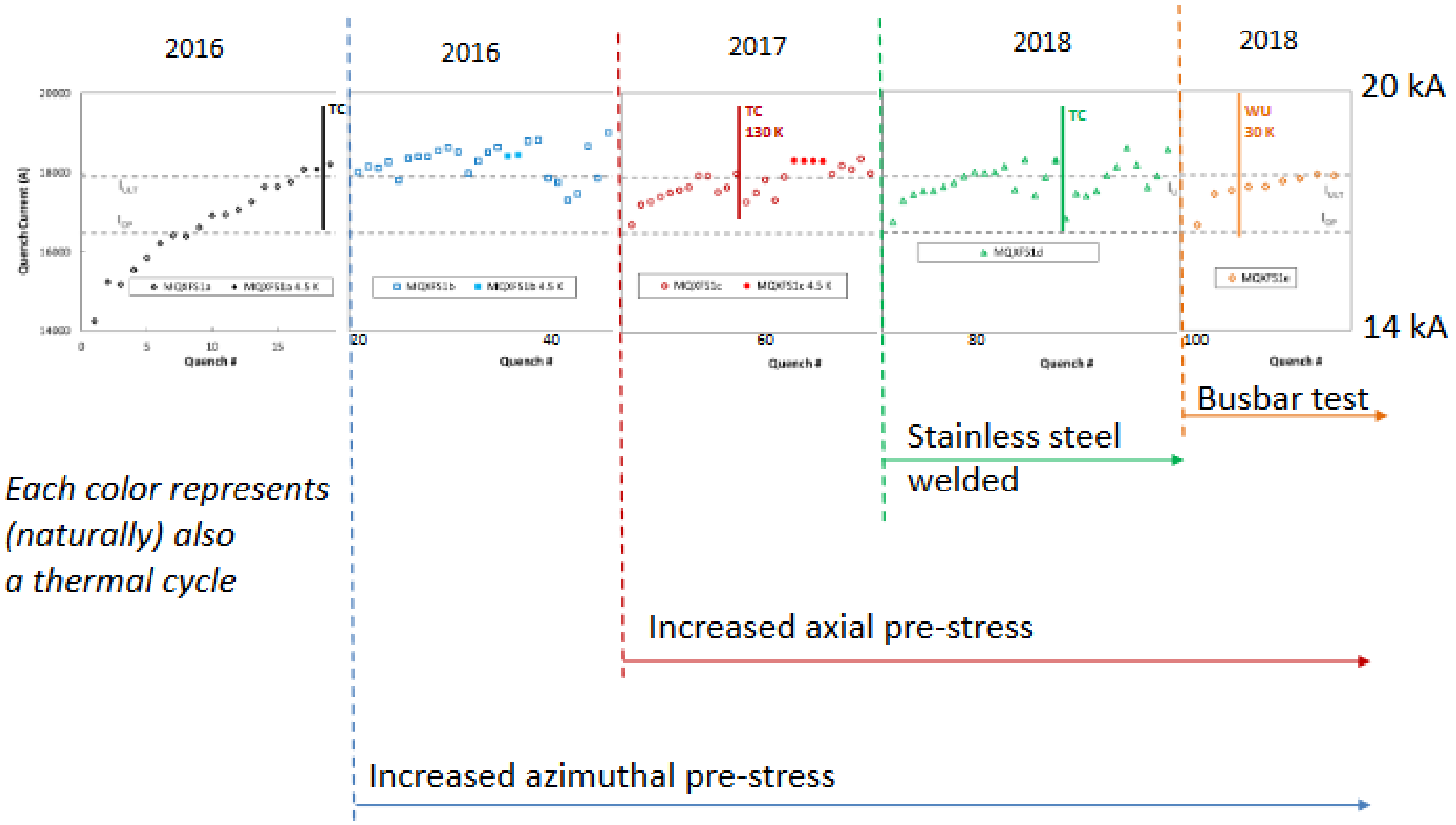
If not "samples" - magnets of training interest

There are magnets that can give invaluable contributions to Training investigations: magnets that retrain "the same way" and thus, covering all:
"Reproducibility", "Statistics", "Timing", "Simplicity", "Cost"

For the last three TCs the magnet showed very good retraining repeatability.
However, projects have other priorities and I did not manage to "save" the AUP magnet for future testing (it is still usable but it requires efforts + funding to make it a testable object).

Initial testing with it was proposed ("officially") in 2020

LARP/AUP : reproducible training of MQXFS1 after 2016



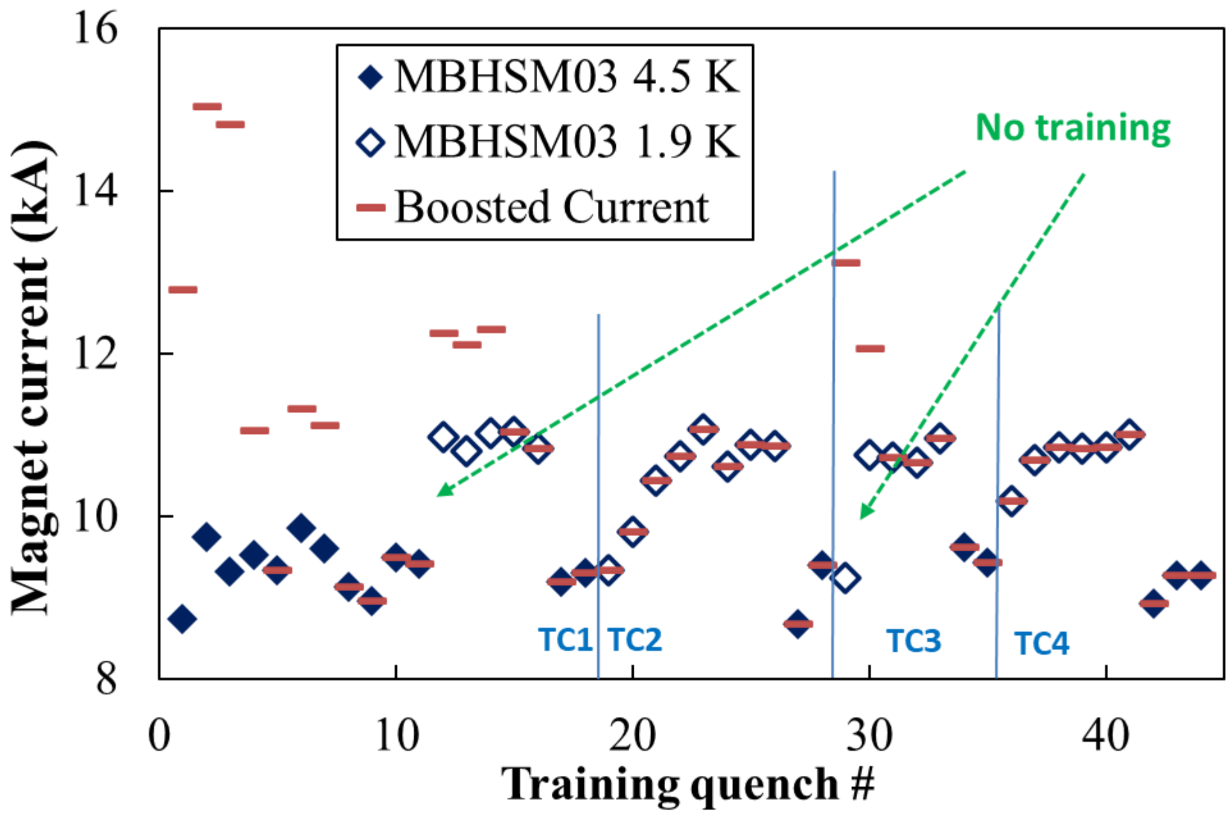
If not "samples" - magnets of training interest

There are magnets that can give invaluable contributions to Training investigations: magnets that retrain "the same way" and thus, covering all:
"Reproducibility", "Statistics", "Timing", "Simplicity", "Cost"

Retraining is obvious but TC2, TC4 are only partially similar and it is not clear if such behavior will continue.

So, a key aspect is questionable – repeatability.

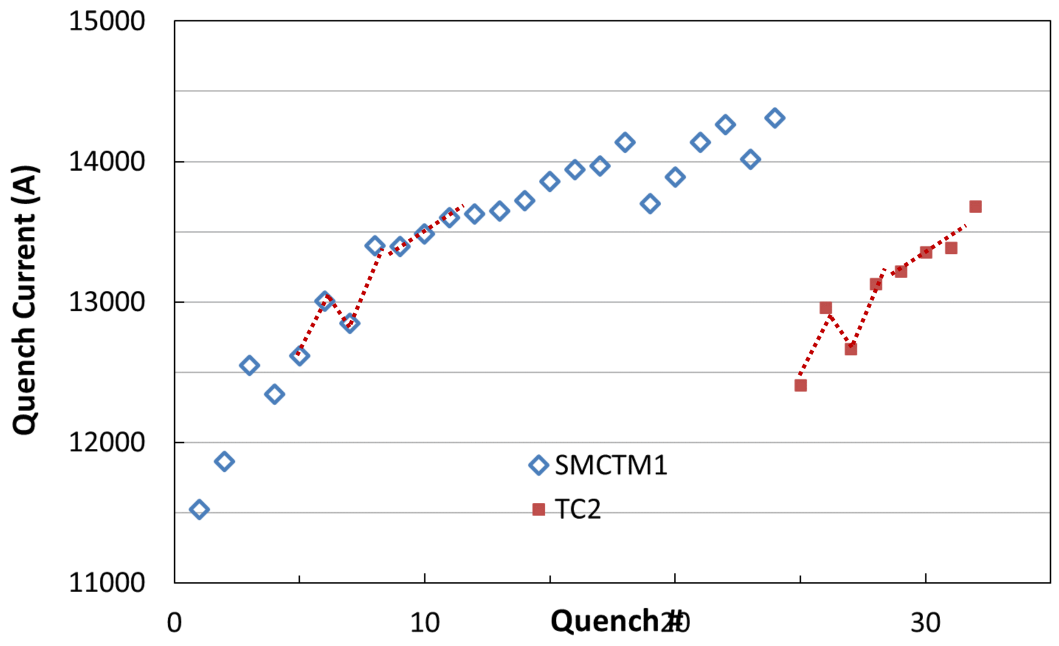
11 T: MBHSM03 – training in TC2, TC4



If not "samples" - magnets of training interest

There are magnets that can give invaluable contributions to Training investigations: magnets that retrain "the same way" and thus, covering all:
"Reproducibility", "Statistics", "Timing", "Simplicity", "Cost"

SMCT: SMCTM1 (TC1, TC2)



SMCTM1 may be another candidate…
(this is one outer coil).

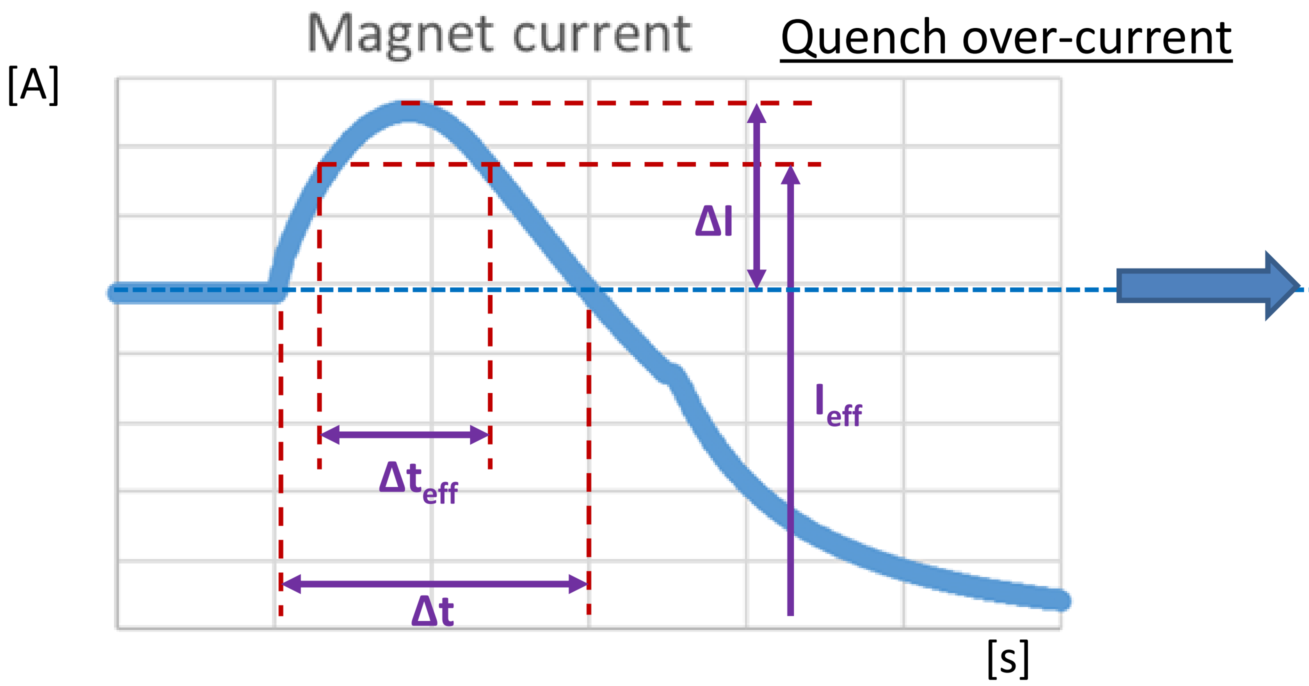
Retrainable coils are very valuable.

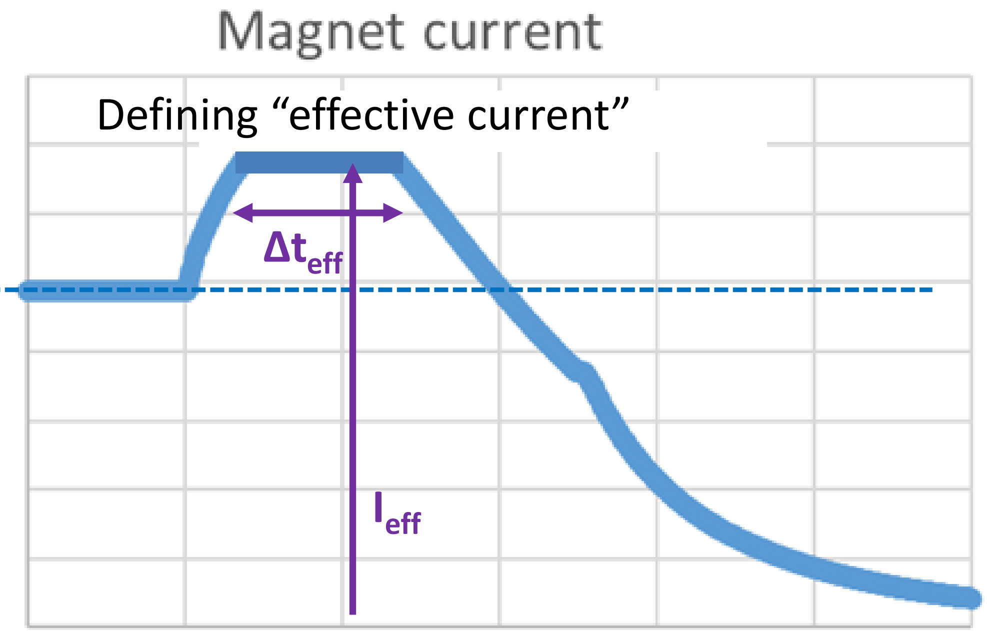
It is worth considering using them for dedicated training studies

However: **"General", "Local, "External", "Synergetic"**

Even in the best-case scenario using few retrainable magnets is only a part-solution (albeit, quite useful one)

Using available tools for *scientific* development





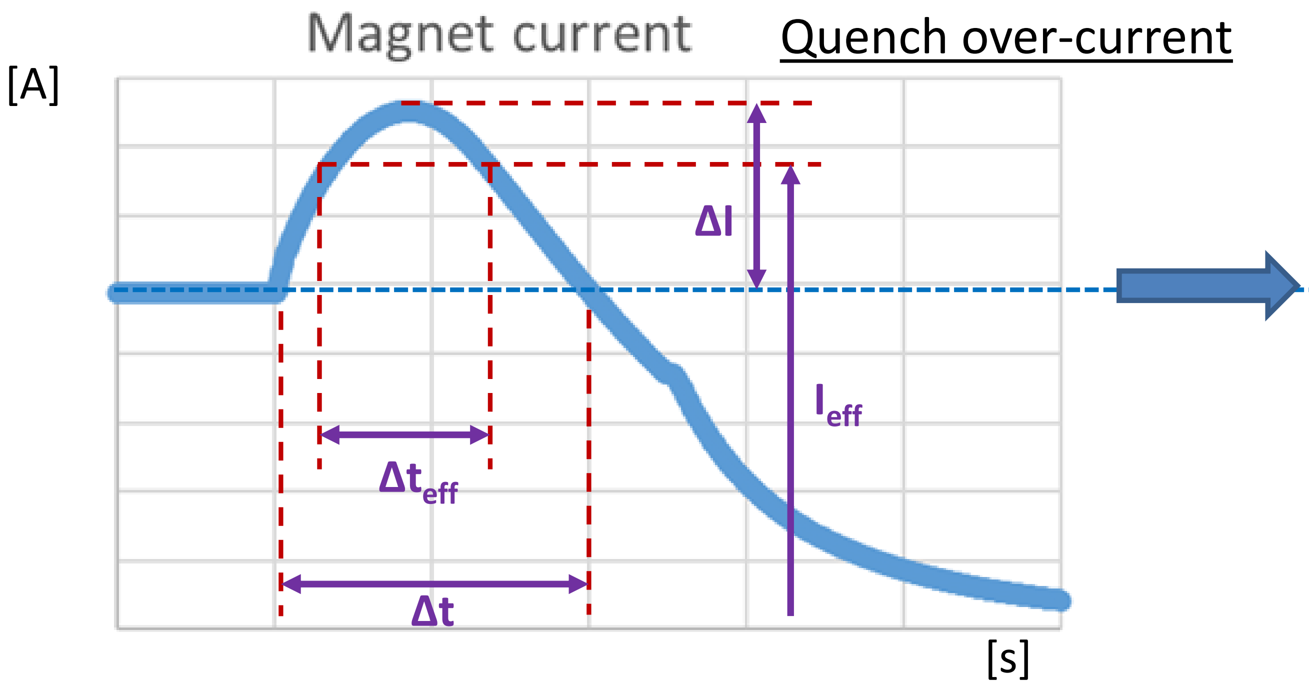
By definition, the effect on training should be the same from currents depicted in the two plots. Introducing "effective current" takes out the uncertainty of the shape but it doesn't help to measure anything yet. It is unlikely that the "effective current" is equal to the peak current.

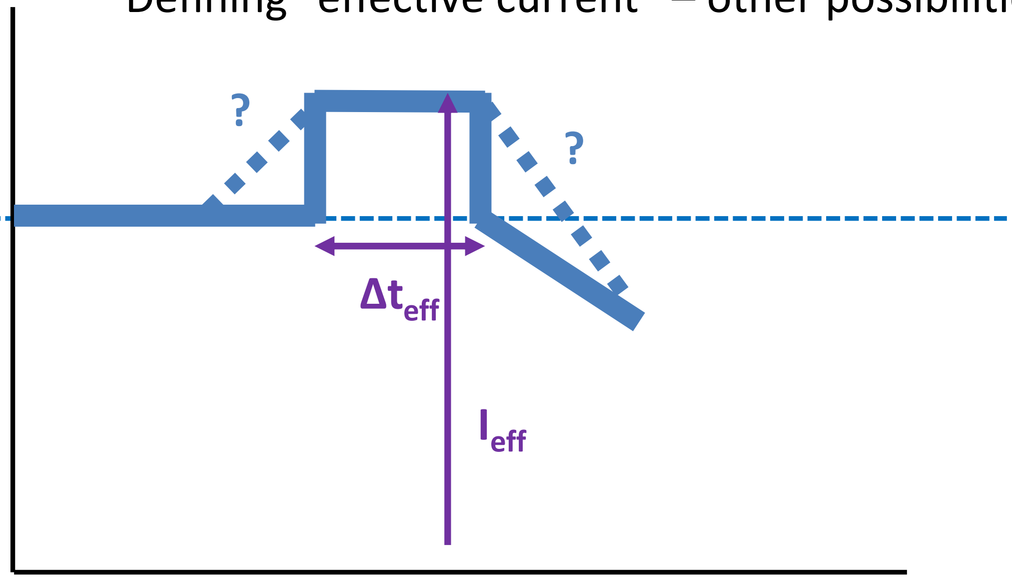
In simplified terms,

Training "T" is affected by quench over-current which means that it must be some function of the overcurrent ΔI and its duration Δt : **T = f(ΔI, Δt)** .

Most likely, it is the "effective current" that matters : **$T = f(I_{eff}, \Delta t_{eff})$**

Using available tools for *scientific* development





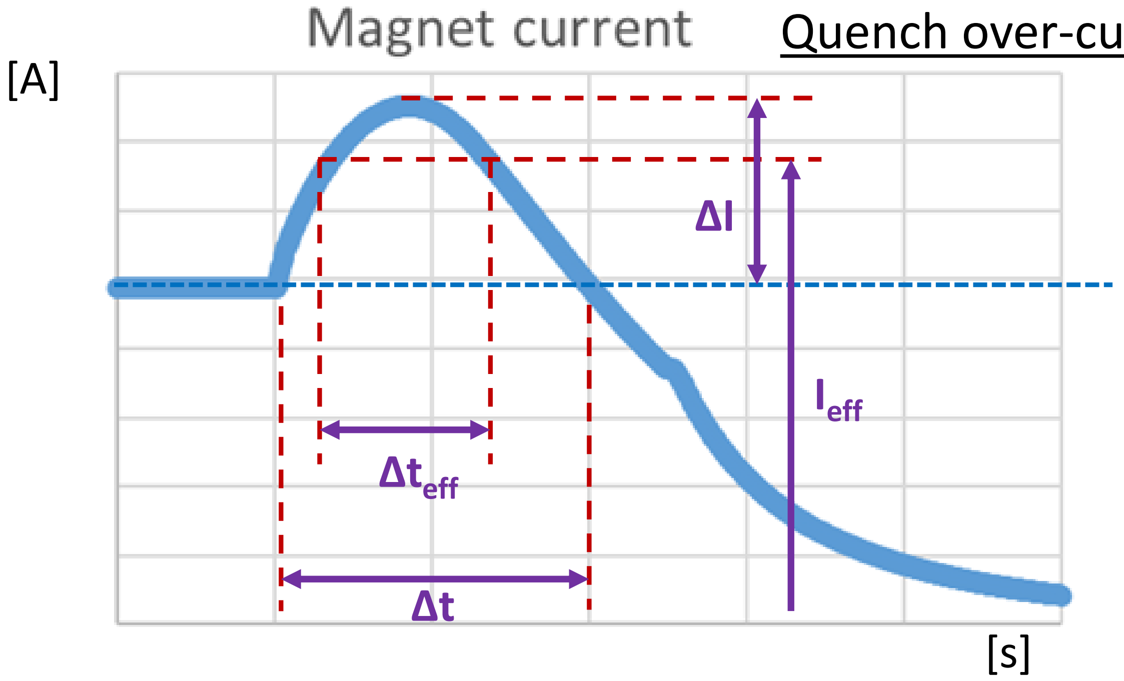
<u>In simplified terms,</u>
Training "T" is affected by quench over-current which means that it must be some function of the overcurrent ΔI and its duration Δt : **T = f(ΔI, Δt)** .

Most likely, it is the "effective current" that matters : **T = f(I_{eff}, Δt_{eff})**

Very limited number of measurements (with CLIQ) so far suggest that Δt_{eff} should be at least **10-15 ms.**

Yet, we don't really know what "effective" really means.

Using available tools for *scientific* development



Quench over-current

QCD allows to change ΔI and Δt (not independently) on a randomly sophisticated sample/magnet model.

It hasn't been used since its first use more than 2 years ago and there was no expressed interest of using it.

Assuming the shape is of a second order importance,

- What is the minimal time Δt /Δt_{eff}/ that affects training?
- Is it consistent with current transient models (change of inductance, etc.), what needs to improve?
- What input does it provide to models?
- What drives the minimal Δt /Δt_{eff}/ value (quantitively)?
- What information does it reveal about force distribution + evolution and training/quench phenomena?
- What is the physical (and practical) meaning of "effective"?
- What is the role of temperature?

(discharges at 300 K/ 78 K, as Steve K. was wondering?)

Magnet/sample "testing" – it is about "variations"

- In R&D magnet series we aim to change something, like (pre-)stress, and observe the effect
- With "samples", we'd do exactly the same
- With QCD we would change time duration of Lorentz forces (and ramp times)
- With re-training magnets, we would still change some conditions (T? A/s?) and see the effect on re-training

- All cases are about variation of conditions

- **Friction in coils (interfaces) is another condition and it could be changed by mechanical vibrations**
  - **Changing friction that way, instead of others, satisfies**
    "Reproducibility", "Statistics", "Timing", "Simplicity", "Cost"

("simplicity" requires some development in that case before one can really claim it)

  - Still, "vibrations" have a lot of faces –
    from "hammer hit" to "music" – and thus different exploration thrusts

Exploring induced mechanical vibrations in superconducting magnets

Stoyan Stoynev (Fermilab)

Mar 31, 2023

DOI: 10.2172/1969685

Report number: FERMILAB-TM-2802-TD

https://inspirehep.net/literature/2647507

AIIIe-M10	Design of a dedicated device/technique using vibrational methods	Apr-25	In progress	Apr-25	
		S. Stoynev	Activities progressing slowly due to level of priorities (Mike K. + students)		

Ultimate program about “training”

The most expensive “proposal” in **2017/2018**: 2. **Wire → magnet training program** → Let’s talk about it

If we can not make something train less (or not train) can we control it to train worse and navigate from there?

- Paradigm shift : start with something that doesn’t train and make it train in discernable steps
- Start with simplest objects (wires)
- Continue by systematically elaborating them but link with previous step(s)

“Reproducibility”, “Statistics”, “Timing”, “Simplicity”, “Cost”

- Eventually built (small) magnets for training purposes

- I know of efforts to do any of the single steps above but not a concerted effort to walk the whole way
- I would argue that without a complete “program”,
  contributions to “science” are minimal (yet could have great engineering effect at times)

“General”, “Local, ”External”, “Synergetic”

Such a comprehensive program is unlikely to be developed without **“General”**

#1 (information generation)

The Process of Solving Complex Problems

Andreas Fischer, Samuel Greiff, and Joachim Funke[1]

Systematic strategy selection on the solution process

(1) information generation (due to the initial intransparency of the situation), (2) information reduction (due to the overcharging complexity of the problem's structure), (3) model building (due to the interconnectedness of the variables), (4) dynamic decision making (due to the eigendynamics of the system), and (5) evaluation (due to many, interfering and/or ill-defined goals).

- Whatever we do, #1 (above) lays the foundations for progress
- Information reduction (#2) is about suppressing irrelevant data not about minimizing data taken
- For us #1 is about testing but also about instrumentation – QA, acoustical sensors , coil voltages, optical fibers, temperature sensors, strain gauges, … - and quality of data (noise, resolution, coverage)
- If those are not properly designed and streamlined our **information generation** and adequate use of it is questionable

Conclusions

- Any successful R&D effort will need at least one (better more) of those supporting pillars:

"General", "Local, "External", "Synergetic"

- Any instance of critical development better rely on all development beams:

"Reproducibility", "Statistics", "Timing", "Simplicity", "Cost"

If an area needs to be developed, conditions on the left better be met. On the other hand, it is cheaper to be an "observer" or/and rely on potential "silver bullets" (it is a viable strategy).

- Progress is impeded when pillars and beams are missing, "management" sets the scene as appropriate
- The above determine the **plausibility** of R&D success

if something doesn't happen, then most likely conditions are unfavorable

---

plausibility

probability

*Opinion: we will never find the **probability** of R&D success in a closed system with both project-based frame of thought and conflict-of-interest inevitably present*