SRF Long Operation Experience and Issues to Be Resolved

A collection of "features", challenges, and vulnerabilities and some "lessons learned"

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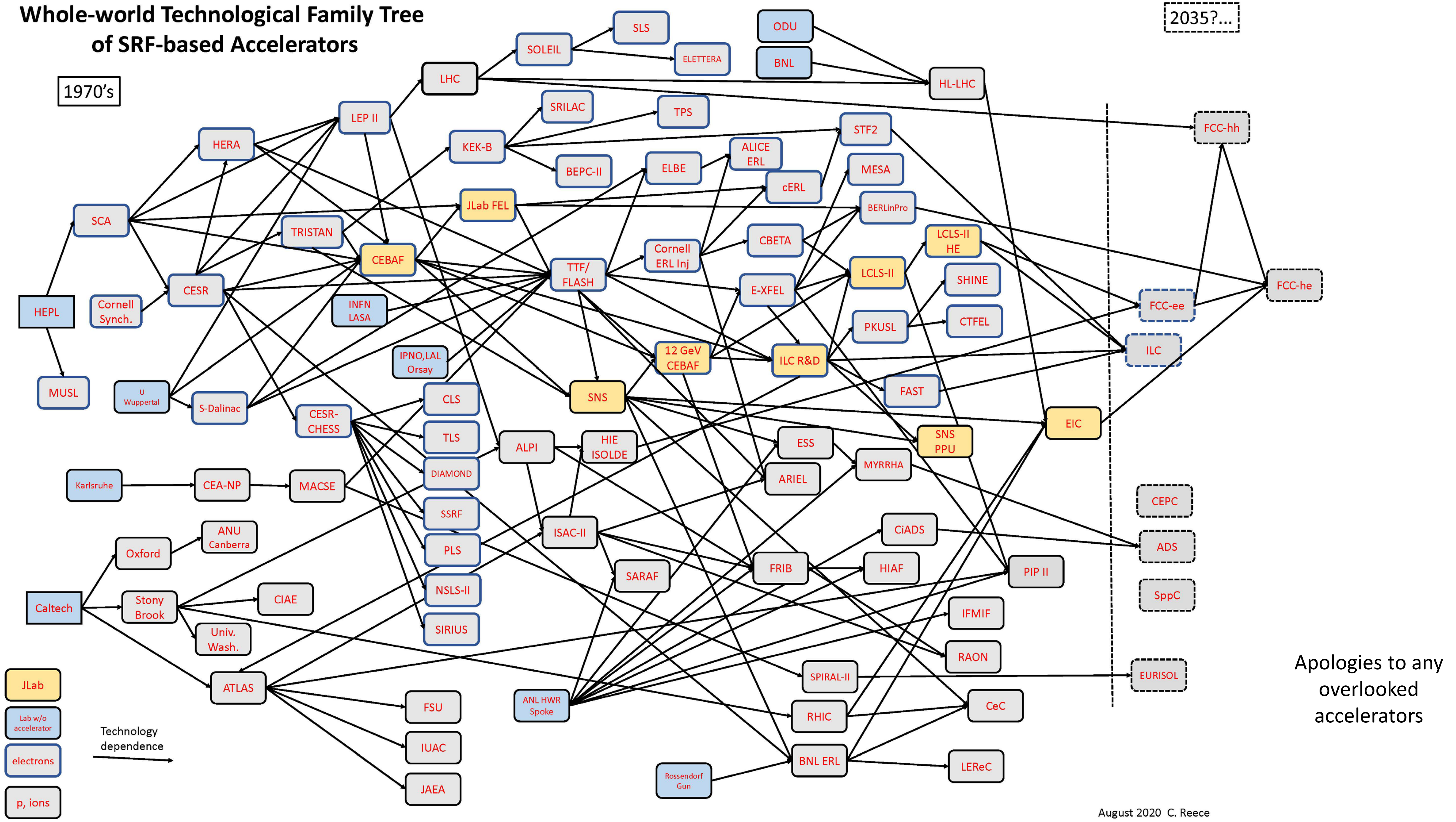
SRF Long Operation Experience and Issues to Be Resolved

- **SRF technology applied to accelerators is wonderfully complex**
  - Inherently multi-disciplinary
  - Huge number of coupled parameters – everything matters
  - If you like simplicity – *find other work*
  - Remember that cost-effectiveness drives everything
    - Research, design, fabrication, processing, maintenance, operation
    - Nothing is cheap
    - We only do this because there is no better way to meet the need
  - Designs build upon previous design and operation experience
  - Learn from the insights, successes, and difficulties of others
  - Accumulated physical understanding is **required** for engaging unexpected problems

Whole-world Technological Family Tree of SRF-based Accelerators



SRF Long Operation Experience and Issues to Be Resolved

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- **I will attempt to share examples of problems encountered, understanding gained, and lessons learned.**
- **These are the issues that we wish we didn't have to deal with, but we do.**

  - Operational limitations
  - Durability limitations
  - Peculiar unexpected couplings
  - Contamination issues and standards

Warning: plenty of words, shy on pictures, imagination required

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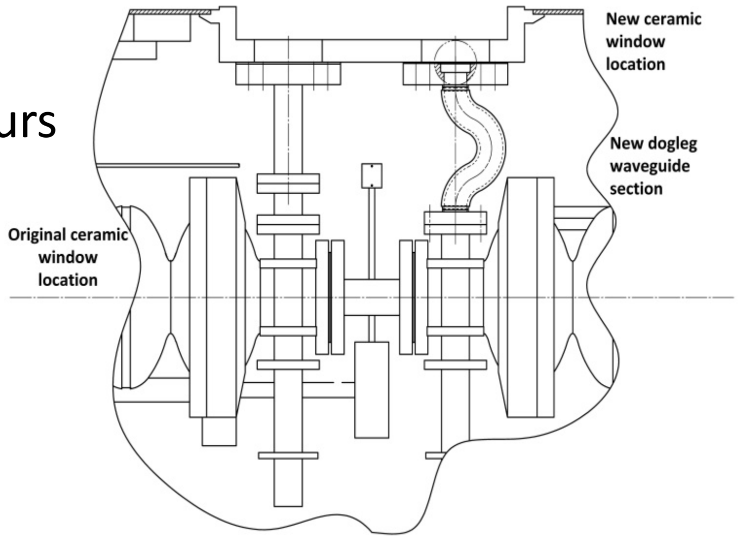
- **#1 – CEBAF cold ceramic RF window**
  - 1985 design choice – hermetically sealed pair of 5-cell cavities – (era of 5-12 MV/m)
  - Qualify a pair in vertical test, then keep under vacuum through assembly and installation.
  - **Requires a waveguide RF window** – at 2 K, very near the beamline – what could go wrong?
  - 2 K ceramic has very high bulk resistivity.
  - Accumulates static charge in the presence of electronic activity – field emission + secondaries + photoelectric charging by x-rays.
  - Eventually there is a discharging arc – which trips RF and beam delivery.
  - At some gradient, ~80% of original 1993 CEBAF cavities had this issue Resulted in cavity-specific gradient-dependent arc rate: ranges from hours to several days.
  - The individual cavity behavior was parametrized (Jay Benesch).
  - Factored into the linac gradient distribution algorithm to minimize the integrated arc trip rate.

    >> For many years this has been the primary operational constraint on CEBAF energy for physics.

    >> Reworked cryomodules now move this ceramic window out, beyond a dogleg in the waveguide.



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- **#2 – Small leaks matter**
  - CEBAF original cryomodules use many **indium wire gasket seals**.
  - These gaskets rarely leak, once positively sealed.
  - Cryomodule in NL 11 zone – rare instance of LHe leak into beamline vacuum
  - The 2 K helium leak was small.
  - Took 3-4 weeks to accumulate one monolayer of helium on the cold cavity surfaces.
  - During this time cavities ran fine and supported beam delivery.
  - Then pressure would begin to rise on beamline ion pumps in response to RF and trip interlocks.
  - The voltage from the cryomodule was required for the physics program.
  - **Solution:**

    >> "Burp" the cryomodule ~once per month by warm up to 25 K, with turbopump on beamline.
    - Ran this way for 6-8 months, then removed the CM and repaired the leak.

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- **#3 – Even the dehumidifier**
  - CEBAF cryomodules have rotary feedthroughs to drive cavity tuners.
  - A control loop tracks cavity resonance to compensate for detuning effects, e.g. He bath pressure.
  - It was noticed that multiple cryomodules at one end of the South Linac showed coherent tuning swings with ~1.5 hour period. Creating excessive tuner operation.
  - **What's going on?**
  - Close inspection of the tuning datalog revealed a phase shift in the tuning cycle, with a particular zone going first.
  - Standing in the linac at that spot scratching my head, I noticed a **cool breeze** blow over my shoulder.
  - The tunnel dehumidification air conditioner was cycling excessively, sending a wave of cold air.
  - The waveguides feeding each cavity have resonant filters on them to absorb klystron harmonics.
  - These components were provided by the "**low bidder**" and have high *temperature sensitivity* to their tune.

  >> The waveguide leg had a temperature-dependent reactance – adding a slowly changing phase shift in the resonance tracking loop!

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- **#4 – Vacuum matters**
  - What vacuum is good enough? – for how long?
    - Anticipate managing your gas load, whatever it is.
    - Beware of inadvertently using SRF cavities as critical cryopumps.
  - Normal ion pumps eventually become particulate sources – beware of accumulated gas load.
  - CEBAF has not been baking-out adjoining warm beamline sections – so *cavities pump everything*.
  - Note that hydrogen and helium are quite mobile with just a little added heat.
  - CEBAF has had issues with **hydrogen outgassing** from the newest C100 CMs, eventually becoming unstable for RF and vacuum interlocks.
    - Though not "leaks", the only solution was to "burp" the accumulated hydrogen in a thermal cycle.
    - Avoid by hydrogen "degas" bakeout of all stainless steel beamline elements.
  - Temperature bumps on CM shield circuit releases adsorbed gas from thermal transition regions.
  - Dark current generated by field emission **adds heat and releases adsorbed gas** at the ends of CMs.
  - These phenomena can produce delayed vacuum/rf interlock trips **during operations** – when nobody in the control room has a clue about the cause.

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- **#5 – Changing cryoload**
  - Note that field emission **deposits heat** wherever the electrons hit.
  - Contamination easily spoils the SRF cavity *Q* via this mechanism >> plenty of extra heat.
  - Superfluid **LHe** has wonderful properties, but it has **limited heat conduction capacity**.
  - This conduction limitation decreases as T rises – so factor that into your design.
    - Cavity "helium riser" pipe size has a maximum heat conduction capacity – else boiling ensues, producing huge microphonics, liquid level disturbance, rf trips, beam loss, downtime.
    - CEBAF accidentally built a prototype CM with only ~ 13 W capacity per cavity – oops.
  - Even in vertical test, **cavity in helium vessel is limited by cross-section of fluid**.
    - C100 cavity CW without HV = 42 MV/m, with HV = 32 MV/m max in VT 2 K bath
  - Adequate 60 W design capacity at 2.00 K can degrade to <45 W at 2.10 K – *work **with** cryo-designers*.
  - In addition to cavity specific capacity limits, there are also cryomodule flow capacity limits.
    - Endcan plumbing pipe sizing and valve sizing have significant flow impedance. At high flows, this raises the pressure on the cavities, which raises the temperature, which increases losses…
    - 175 W, 250 W ??
  - Recall that CW operational costs increase ~quadratically with gradient.
    - **Higher gradient is not always cheaper to operate**.

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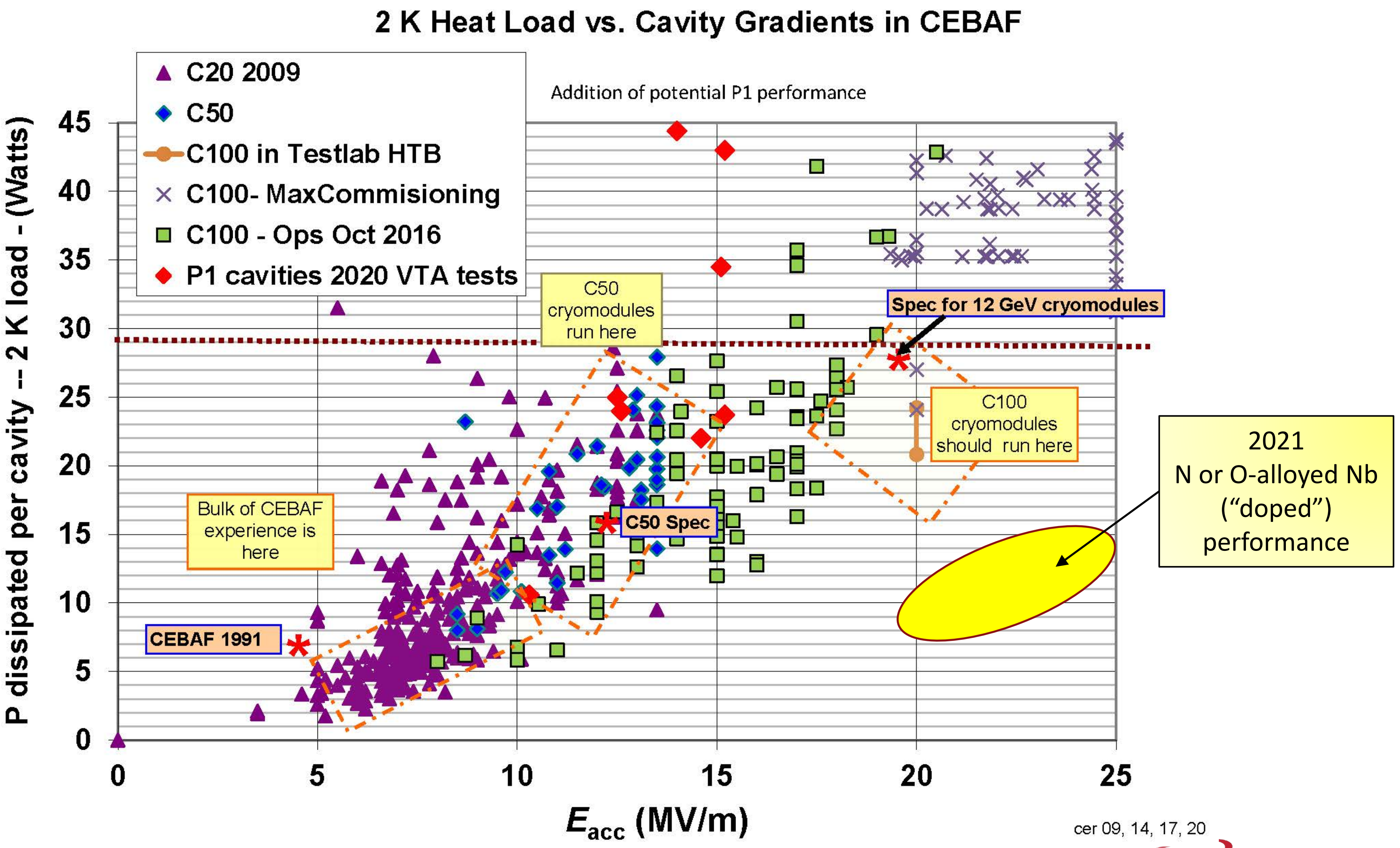
- **#5 – Changing cryoload**
  - Note that CW operational costs are largely driven by **2K watts**.
  - Illustration from CEBAF's past.
  - Don't just brag about *Q*, think about **heat**.



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- **#6 – Practical microphonics**
  - With high-gradient and low current applications, power efficiency pushes preferred Q_L up.
    - Very small bandwidths, < 50 Hz!
  - But anticipated and actual microphonics impact LLRF sophistication and RF power budget.
  - Operational “RF” or “quench” trips may actually be caused by transient microphonics.
  - Challenging to diagnose – fast capture diagnostics are required.
  - Also a challenge when cavities are directly coupled together.
  - **Lorentz force on one cavity detunes its neighbors** – results in a fast cascade of trips.
    - Which one was first, and why?
  - Must understand the **vibrational modes** of the whole cryomodule mechanical system.
    - Design out or damp significant modes.

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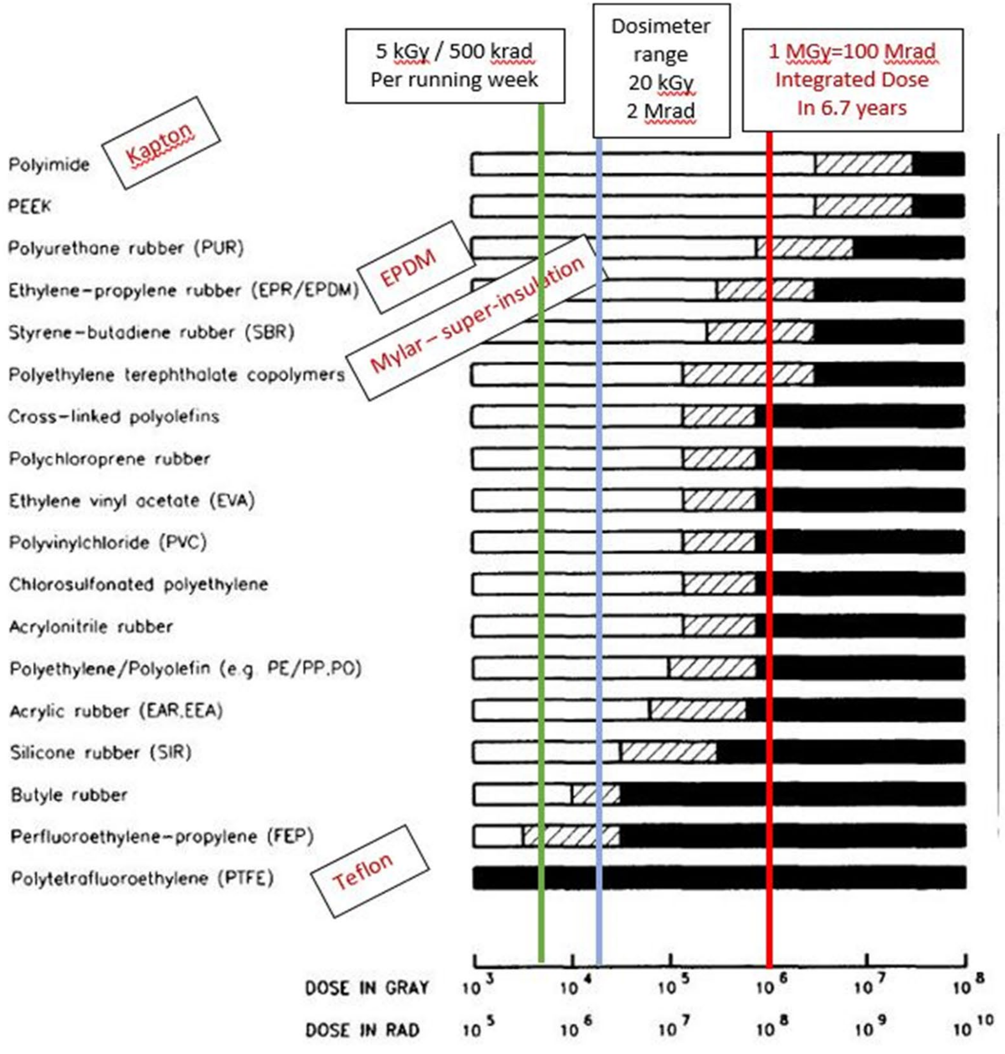
- **#7 – The bane of SRF**
  - **Particulate contamination = bad news**
  - **Metallic dust**, which is very likely to have highly textured surface structure with locally very small radius of curvature, can produce conditions with very large local field enhancement factors which then enable Fowler-Nordheim electron emission from the surface.
  - Such electrons experience the RF fields in the cavity and follow trajectories highly dependent on source location and resonant RF field amplitude.
  - The production of source electrons and thus the consequential x-rays **increases exponentially** with increasing electric field amplitude.
  - Electrons having gained energy greater than ~10 MeV can also stimulate neutron production upon impact on high-Z target.
  - These neutrons are subsequently captured and **result in activation of cryomodule and beamline components** quite independently of beam operations.
  - Significant dark current can result in **very high radiation fields**.

"Be afraid, be very afraid" *The Fly*, 1986

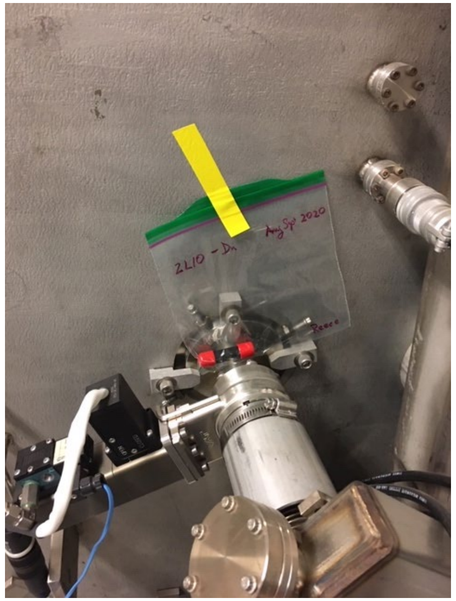
SRF Long Operation Experience

- **#7 – The bane of SRF**
  - **Particulate contamination = bad news**
  - Significant dark current can result in **very high radiation fields**.
  - Placed optichromic dosimeters on beamline of a few CEBAF cryomodules during **5 weeks** of Physics ops 2020.
    - >20 kGy (>2 Mrad) doses observed at several locations
  - This accumulated dose implies an average **sustained dose rates of over 24 Gy/hr (2.4 krad/hr)** exterior to the cryomodule.



CERN 98-01

Appreciation of Damage	Elongation	Utility	
Incipient to mild	75–100 % OF IN. VALUE	Nearly always usable	(open bar)
Radiation index area	25–75 % OF IN. VALUE	Often satisfactory	(hatched bar)
Moderate to severe	< 25 % OF IN. VALUE	Not recommended	(black bar)



SRF Long Operation Experience and Issues to Be Resolved

- **#7 – The bane of SRF**
  - **Particulate contamination = bad news**
  - Significant dark current can result in **very high radiation fields**.

  - **Teflon** is not mechanically stable above only 1 kGy, forget it.
  - **Viton** is significantly degraded by 200 kGy.
  - **EPDM** degrades similarly with ~400 kGy.
  - **EPDM** and **mylar** (used in superinsulation) fall apart (structural disintegration) above 2 MGy, at which dose polyimide (Kapton) begins to mechanically degrade.

  - If we would like for the valve gaskets to have > 6.7 operational service-years, then the implication is that they should receive an accumulated dose of < 300 kGy in that time. This translates into a maximum tolerable radiation dose rate at any valve of **<10 Gy/hr (<1 krad/hr)**.

  - Or pay upfront for very expensive metal-seal valves, and use them infrequently.
  - Note that electronics are **much** more vulnerable.

See also Section 8.7 *Radiation Damage Thresholds* by H. Schönbacher in "Handbook of Accelerator Physics and Engineering", Ed. Chao *et al*.

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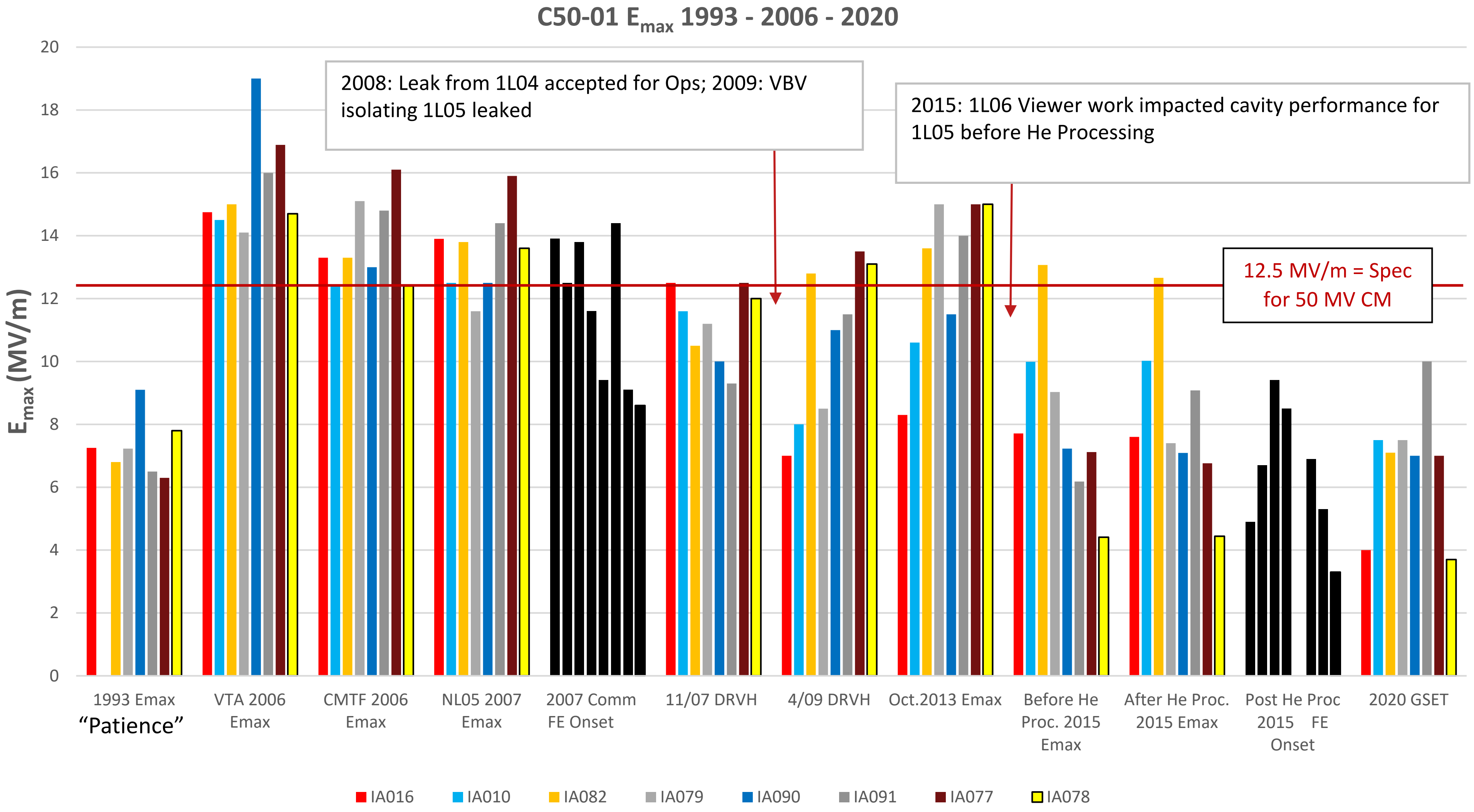
- **#8 – One abused cryomodule – CEBAF C50-1**
  - Degradation due to compounding contamination events



Performance overview: (E_{max} is set by SRF 1 hr stable commissioning, DRVH is operational max, includes rf power and control limitations, GSET is actual beam delivery gradient)

With dogleg shielding cold RF windows, no arcing. So operations turned up gradient into heavy FE >> **first activated** original style CM. (47 mR/hr on contact) Requires added precautions during rework now underway.

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- **#9 – Radiation damage from FE**
  - Several C100 cryomodules performed well as installed.
  - Comparable cleanliness standards were not used for the neighboring warm girder sections.
  - Servicing back-fills were not controlled >> contamination transport into the cavities.
  - Driven hard for physics program >> damaged vacuum valve gaskets >> compounded contamination.
  - Cryomodule C100-9 was severely degraded by a valve failure.
  - On disassembly, the superinsulation (MLI) near the beamline at ends was found severely degraded. Not Good.
  - This strongly suggests that the material in this location has experience above **2 MGy** (**200 Mrad)** integrate dose since installation in April 2013 in and removal for rework November 2020.

MLI from C100-9

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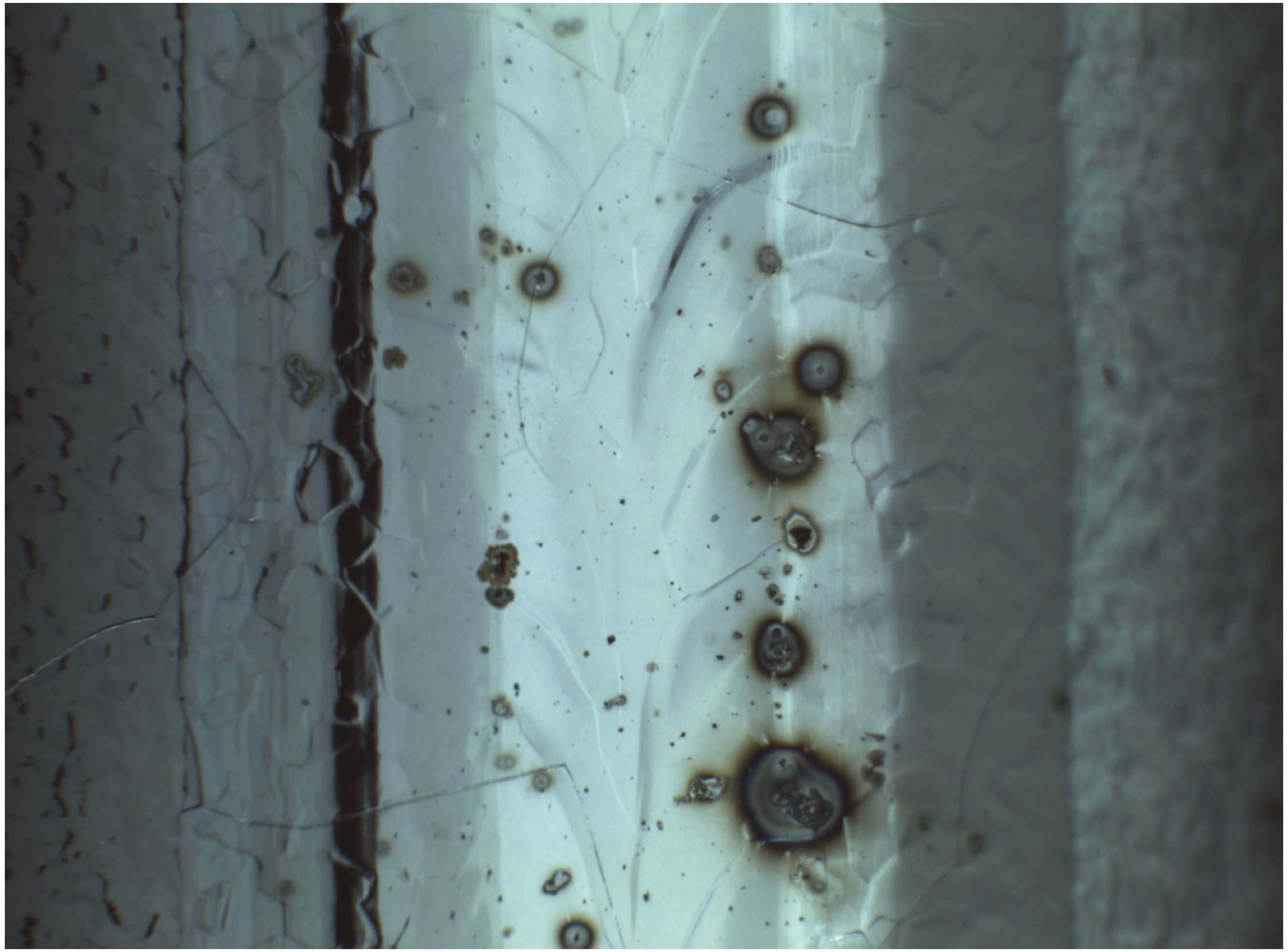
- **#10 – FEL beamline vacuum vent – and frying dust**
  - Cell 4 equator weld region examined ~10 years later
  - Not a field emission issue here, but extreme currents vaporized small conductive particulates that fell to the bottom of the cell.

Photo by Rong-li Geng



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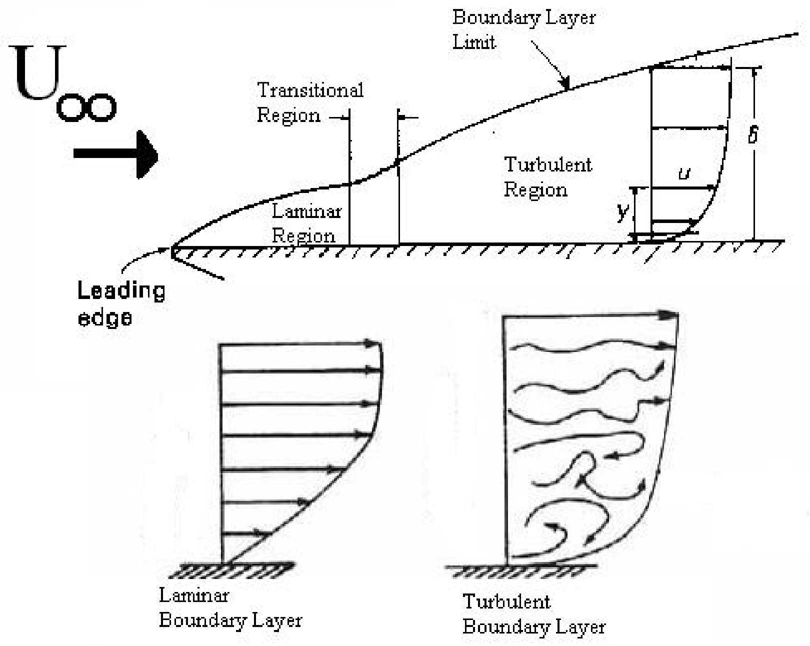
- **#11 – Moving dust**
  - SRF cavity surface - **get it clean and keep it clean** (for years)
  - We want particulate-free surfaces.
  - Ultrasonic with detergent, ultrapure water, UPW high pressure rinse in ISO Class 4-5 environment – these get surfaces clean
  - *Paranoid* precautions to eliminate opportunity for contamination – **are required.**
  - **Engineer process quality assurance – no accidents allowed.**
  - **Must engineer gas flow processes – pumpdown & backfill - to avoid particulate transport.**
  - **Threatening particulates remain suspended** in still air for a long time, so once suspended they move with the gas.
  - All particulates fall out in vacuum.
  - Minimize re-suspension and transport > **ensure no turbulent flow**.
  - With ~ 4 cm ID, this implies 3 NLPM of N_2 (50 mbar-l/s) as maximum mass flow rate.



Kuchnir and Knobloch analysis FERMILAB-TM-1768
K. Zapfe and J. Wojtkiewicz, SRF07, WEP74
M. Böhnert et al., SRF09, THPPO104
Generation and Behavior of Airborne Particles (Aerosols) - CDC

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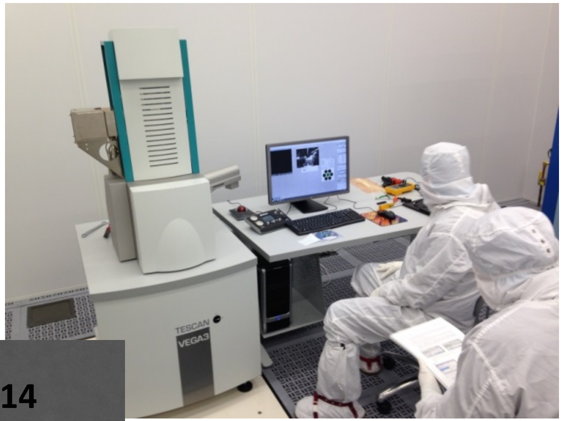
Analysis of particulates from CEBAF

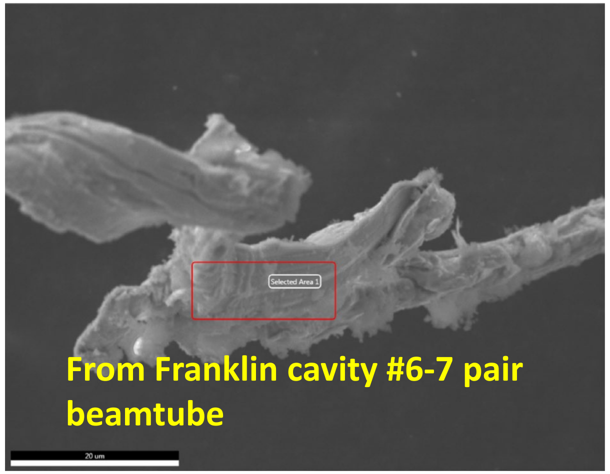
- **#12 – Collecting dust**
  - Systematic particulate sampling (>340) from CM and girders removed from CEBAF
  - Examination using new SEM with elemental analysis
  - Many copper and steel particles found > 40 µm
  - Large assortment of other materials found
  - Clearly inconsistent with current standards
  - Responsible for CEBAF's energy reach limitation
  - Feedback for process improvement

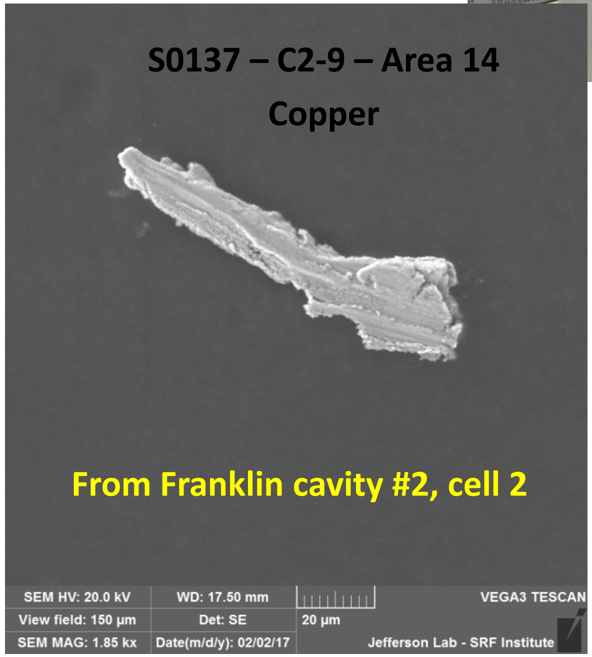


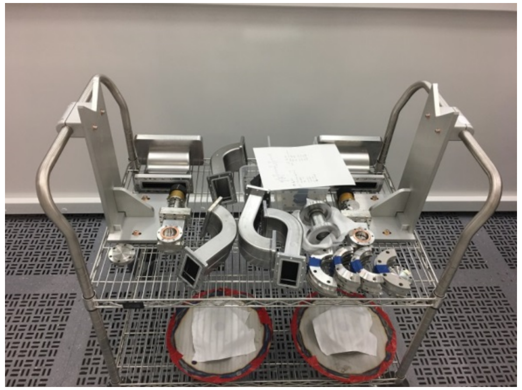
Examples

S0320 - C6-18 - Area 7

Steel







Valente-Feliciano, Spradlin, Trofimova

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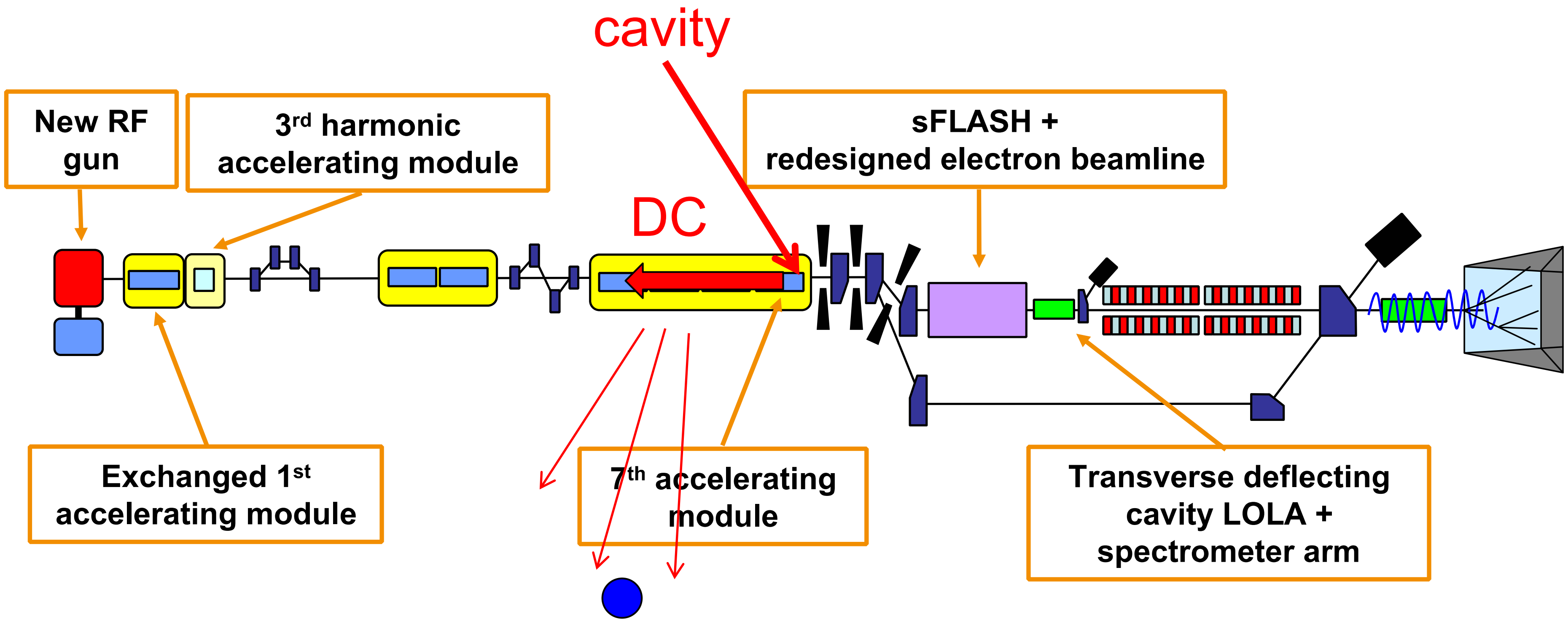
- **#13 – FLASH experience**
  - Cavity 8 in module ACC7 began generating up-stream dark current radiation after input coupler was adjusted November 2015. Significant current at 21 MV/m, no radiation at 14 MV/m.
  - Operational adjustments have accommodated this, running C8.ACC7 detuned, stable now 5.5 years.



Pandora personnel safety radiation monitor (outside of shielding)

From Nick Walker

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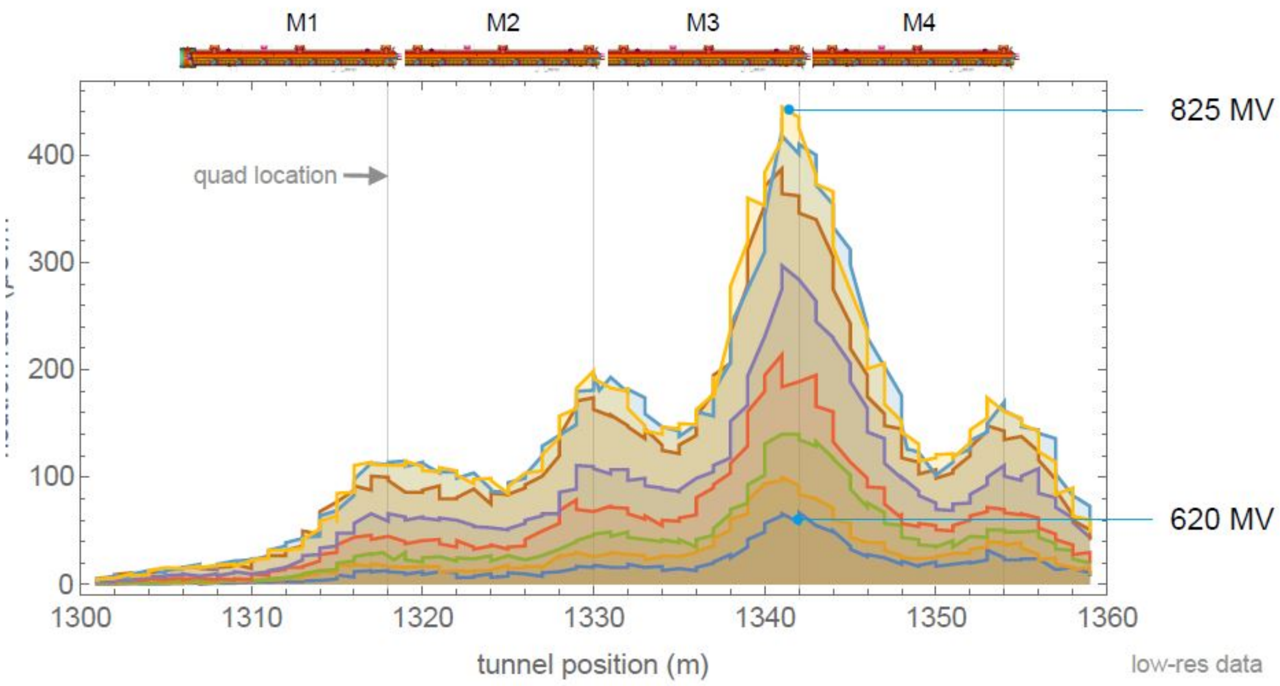
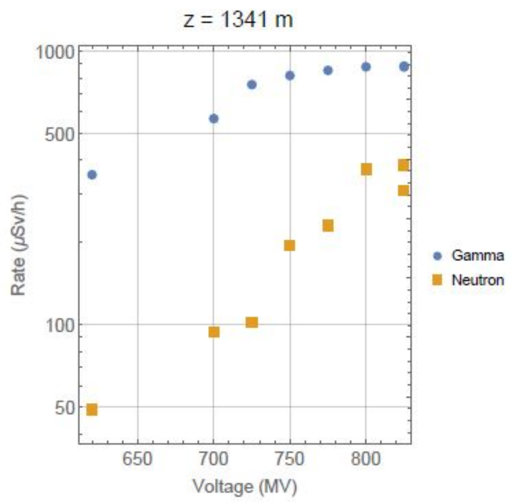
- **#14 – EU-XFEL experience**
  - **Control electronics are in the tunnel.**
  - Administrative limit is **500 μSv/hr** (gammas and neutrons) in tunnel.

Using MARWIN to map RADIATION profile

A23 MARWIN radiation profile scans





From Nick Walker
TTC mtg 2021

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- **#14 – EU-XFEL experience**

Impact Summary

Estimated energy loss due to FE activation during ~2 years operations

Station	Date	Action	Est. Loss	Comment	
A9	13.06.2018	VS reduced	100 MV	MARWIN 500 µSv/h limit	*possibly as installed*
A6	11.10.2018	VS reduced	100 MV	Mutiple breakdowns → high radiation	*operationally degraded*
A7	21.11.2018	M1 C7 detuned	5 MV	Partially compensated. Quench limited but suspected FE driven.	*operationally degraded*
A24	25.10.2019	M2 C7 detuned	15 MV	FE spontaneously activated	*operationally degraded*
A22	14.01.2020	M4 C3 detuned	20 MV	FE spontaneously activated	*operationally degraded*
A23	12.02.2020	VS reduction	40 MV	MARWIN 500 µSv/h limit	*possibly as installed*
A18	23.09.2020	M3 C4 detuned	20 MV	FE spontaneously activated	*operationally degraded*

One breakdown even "fried" Marwin - RIP

very rough estimate needs cross-checking

Total reduction: ~ 160 MV (in 2 years, confirmed degradation during operations)

From Nick Walker TTC mtg 2021

More immediate impact of radiation is on the tunnel electronics (SEUs, trips, etc.)

☞ **"XFEL operational experience" Julien Branlard** (tomorrow plenary)

DESY.

13

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- **#15 – We learn to do better.**

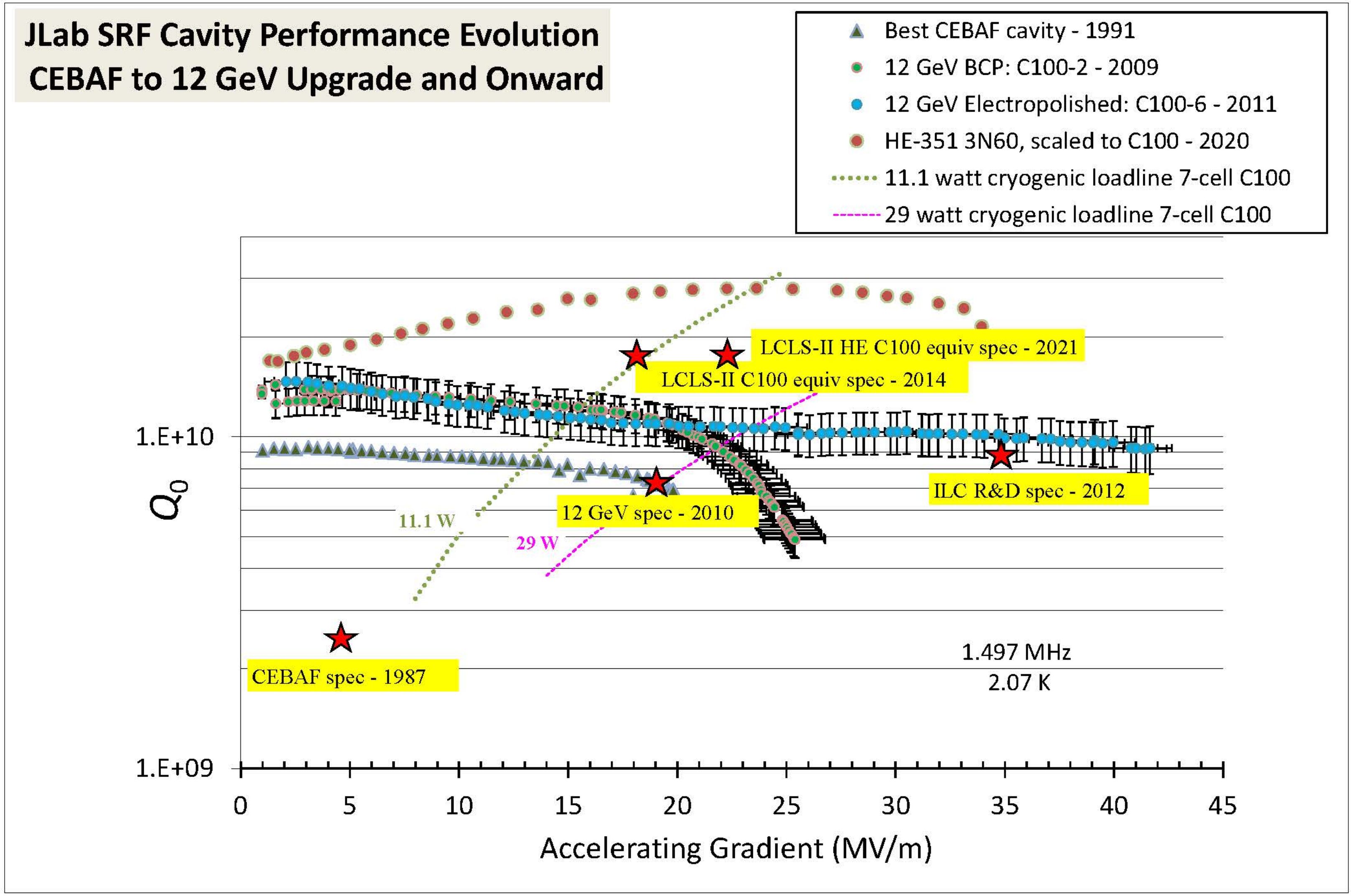

Illustration from JLab experience, typical of others

Techniques, materials, and processes have improved during the past 30 years.

What will the next step be?

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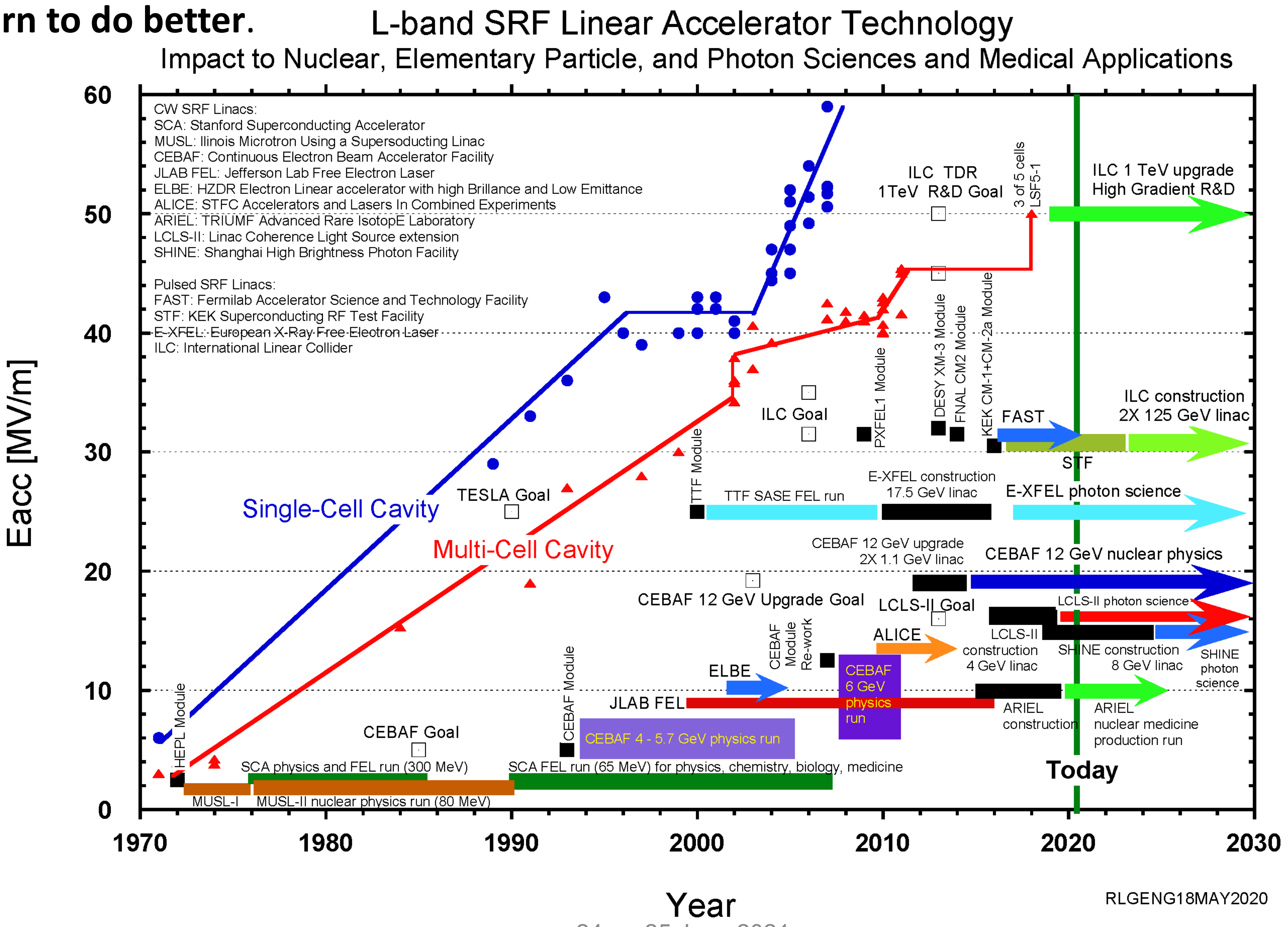
- **#15 – We learn to do better.**



Composed by
Rong-Li Geng

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- **#15 – We learn to do better**
  - While there are many legacy issues, the community continues to learn and standards tighten.
  - The latest CEBAF C100 CM ran 104 MV field emission free, limited by RF power.
  - LCLS-II and the latest “vCM” for LCLS-II-HE demonstrate excellent progress in contamination control.

C1006R – 21 MV/m, CW
(Recovered full performance from contamination by **HPR only)**

HE vCM – 25 MV/m, CW

(To be reported next week)

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SRF Long Operation Experience and Issues to Be Resolved

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    - We only do this because there is no better way to meet the need
  - Designs build upon previous design and operation experience
  - Learn from the insights, successes, and difficulties of others
  - Accumulated physical understanding is required for engaging unexpected problems
  - Contamination can spoil everything.
  - **But when it works right, it makes the amazing possible.**