CEBAF EXPERIENCE WITH FIELD EMISSION

WG2 Field Emission and Its Root Causes

TTC 2025 Meeting, IRIS/IBS, Daejeon

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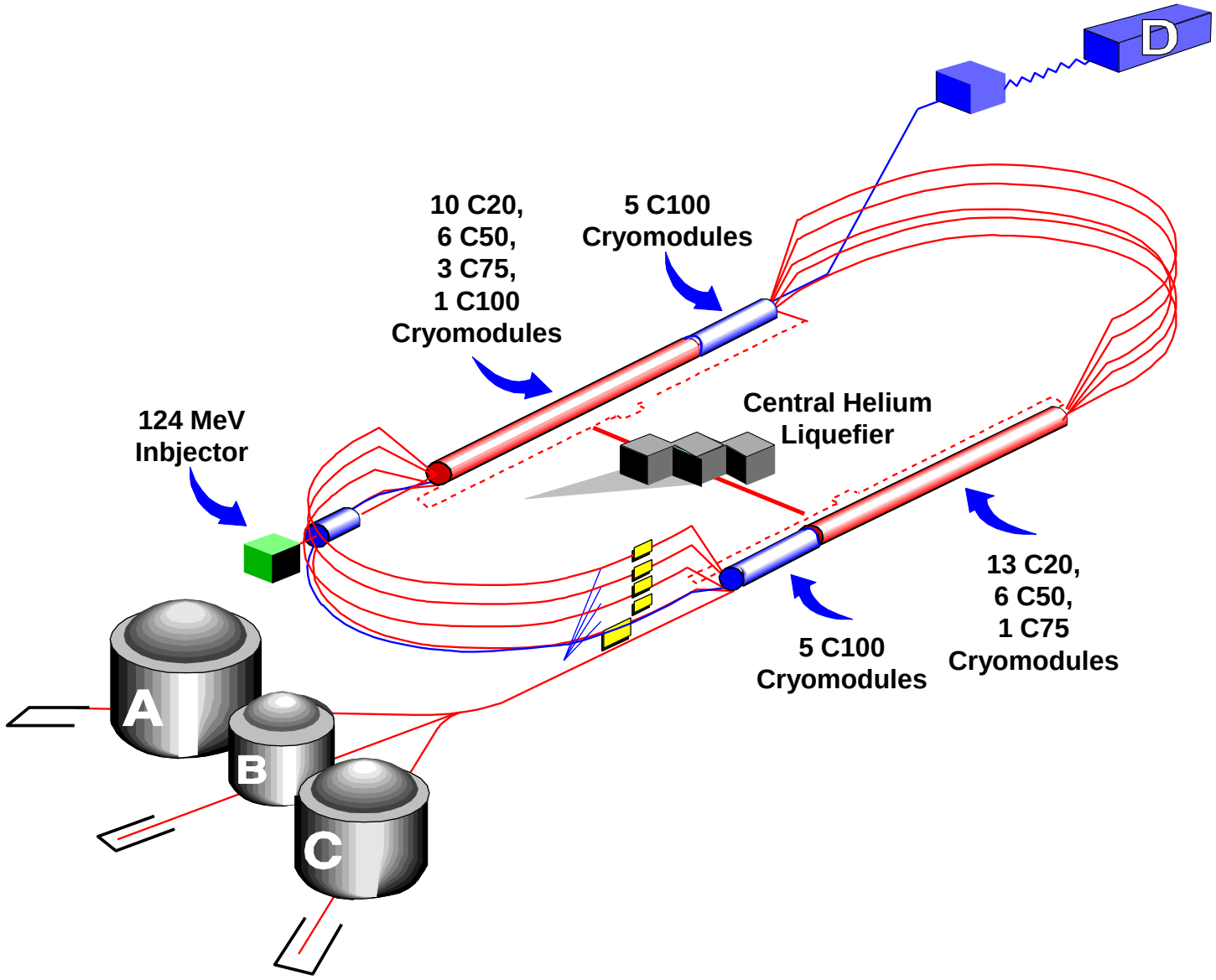
CEBAF – Continuous Electron Beam Facility



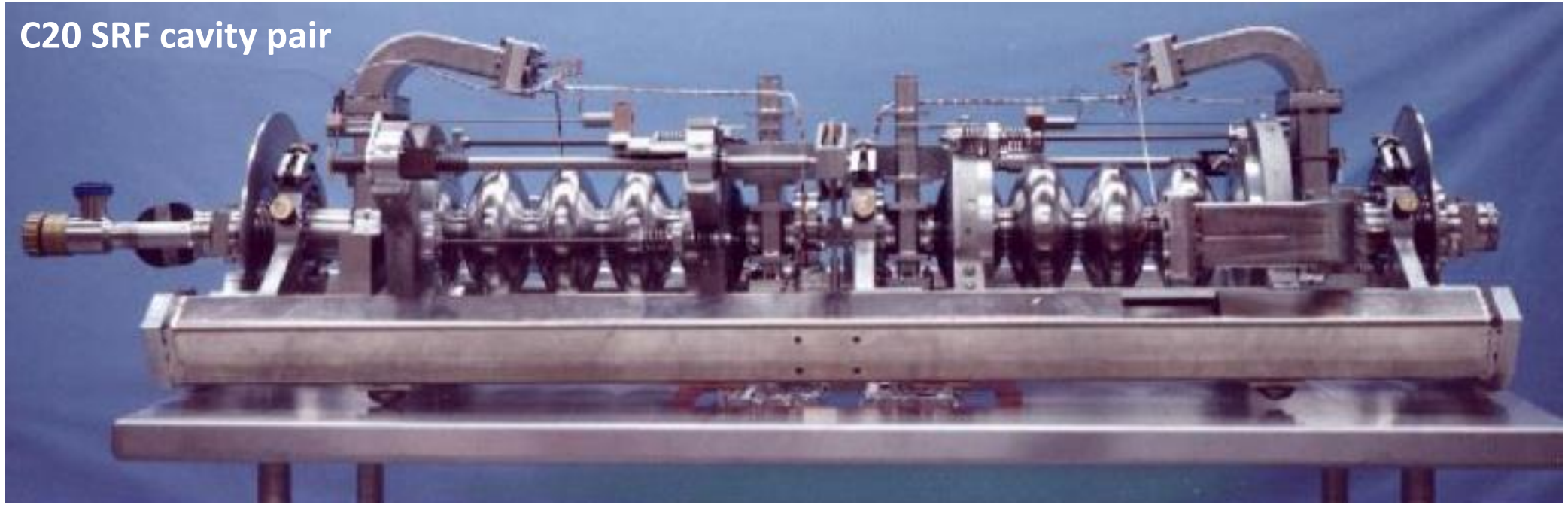
- **Construction start in 1987**
- **First beam on 1 July 1994**
- 4 GeV 200 μA CW e^-
- 5-pass design
  2 linacs x20 C20 cryomodules
- 6 GeV enhanced energy reached in August 2000 after site-wide helium processing

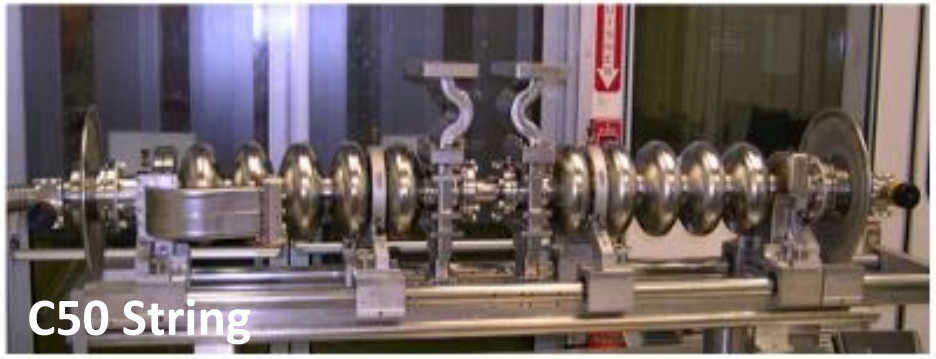
- 12 GeV upgrade adds 2x5 C100 cryomodules and 5½ pass Hall D
- Completed in September 2017
  - I_{max} = 90 mA
  - Pol_{max} ~ 90%
- Simultaneous beam to 4 halls

CEBAF Cryomodule Types

- All cavities are 1497 MHz with waveguide fundamental power couplers with two planer ceramic windows
- All cryomodules are “self contained” cryostats connected by warm beamline sectors
- **C20 – Four cavity pairs in separate cryo-units assembled into one cryomodule**
  - Eight 5-cell cavities per cryomodule, original CEBAF design, 42¼ were installed in the early 1990’s
  - Design gradient 5 MV/m
  - Cavity pair in shared liquid helium vessel including immersed HOM load and tuner
  - 2K glassy carbon HOM loads coupled to cavity with ~3” waveguides.
  - One fundamental power coupler window is at 2 K and adjacent to the cavity.
  - The second (warm) window was originally polyethylene. Upgrading to ceramic windows (3 cryomodules left in South Linac).
- **C50 – Improved performance C20**
  - Rebuild of C20 cryomodules with improved cavity processing.
  - Design gradient 12.5 MV/m
  - Moved the cold window from adjacent to the cavity to the edge of the helium vessel with a dogleg waveguide adapter, that substantially reduced window arcing.
- **C75 – Upgraded C20**
  - Rebuild as C50 cryomodules, reuse cavity end groups, new cell shape, ingot Nb, enhanced cleanness & magnetic hygiene
  - Design gradient 19 MV/m.
- **C100 – 7-Cell cavity using higher klystron power, 8-cavity basic string**
  - Eight 7-cell cavities per cryomodule
  - Design gradient 19.2 MV/m
  - Both fundamental power coupler windows are room temperature ceramic windows.
  - No bellows between cavities to save space and keep length close to original C20 cryomodule design
  - Two ILC style HOM antennas per cavity which are connected to warm RF loads via coaxial cables.

SRF Cavities





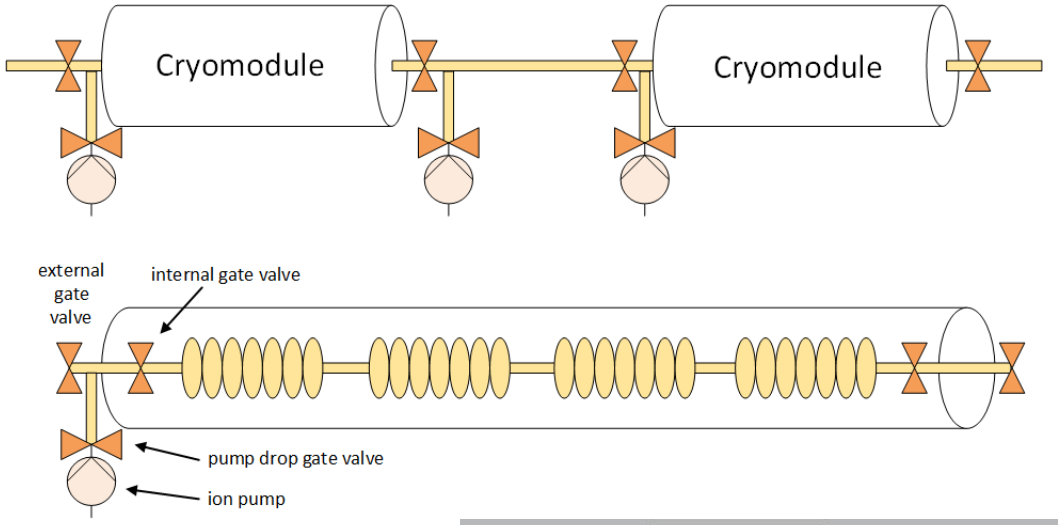
CEBAF Cryomodule Types

Design Parameter	Unit	C20	C50	C75	C100
Energy gain	(MV)	20	50	75	100
No. cavities		8	8	8	8
No. cells per cav.		5	5	5	7
Cell shape		OC	OC	HC	LL
$E_{acc,\ nominal}$	(MV/m)	5	12.5	19.07	17.86
L_{active}	(m)	0.4999	0.4999	0.4916	0.7
Q_0 at 2.07 K		$> 2.4 \cdot 10^9$	$4.6 \cdot 10^9$	$8.0 \cdot 10^9$	$7.2 \cdot 10^9$
$Q_{ext,FPC}$		$6.6 \cdot 10^6$ (± 20%)	$8.0 \cdot 10^6$ (± 25%)	$2.0 \cdot 10^7$ (± 20%)	$3.2 \cdot 10^7$ (± 15%)
R/Q	(Ω)	482.5		525.4	868.9
R/Q per cell	(Ω)	96.5		105.1	124.1
Geometric Factor	(Ω)	274.5		275.6	280.3

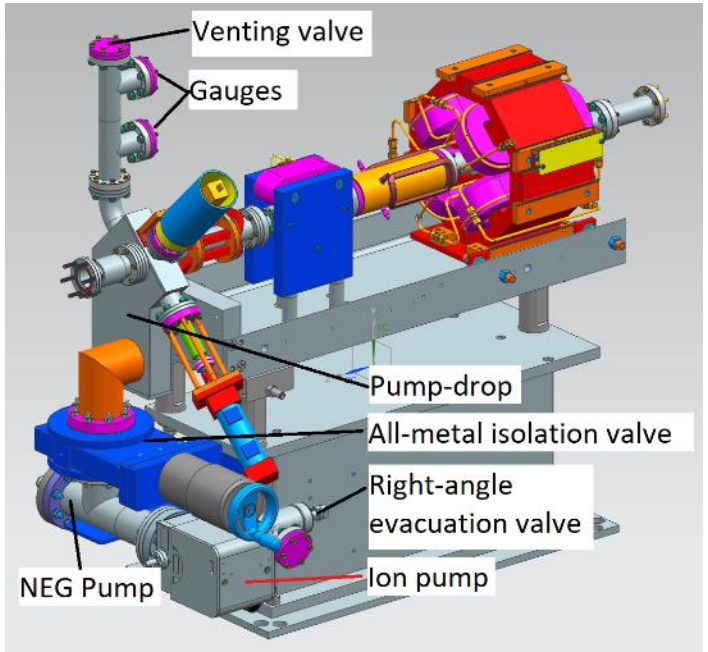
F. Marhauser et al., *C75 Cavity Specifications and Commissioning of the Prototype Cavity Pair*, JLAB-TN-17-055 (2017).
Cell shape: OC = Original CEBAF ; HC = High Current ; LL = Low Loss

CEBAF Original Cryomodule Installation

- **Original cryomodules**
  - each cryomodule has external Viton-sealed gate valves
  - C20-style
    - indium seals with clamped flanges
    - Viton-sealed gate valves in between cryo-units
  - C100
    - aluminium gaskets with clamped flanges
    - all-metal gate valves at cavity string extremities

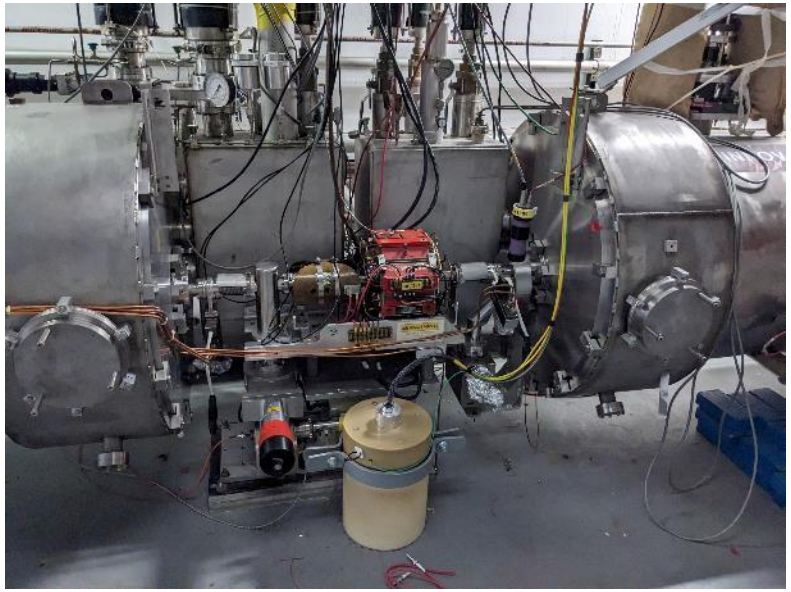


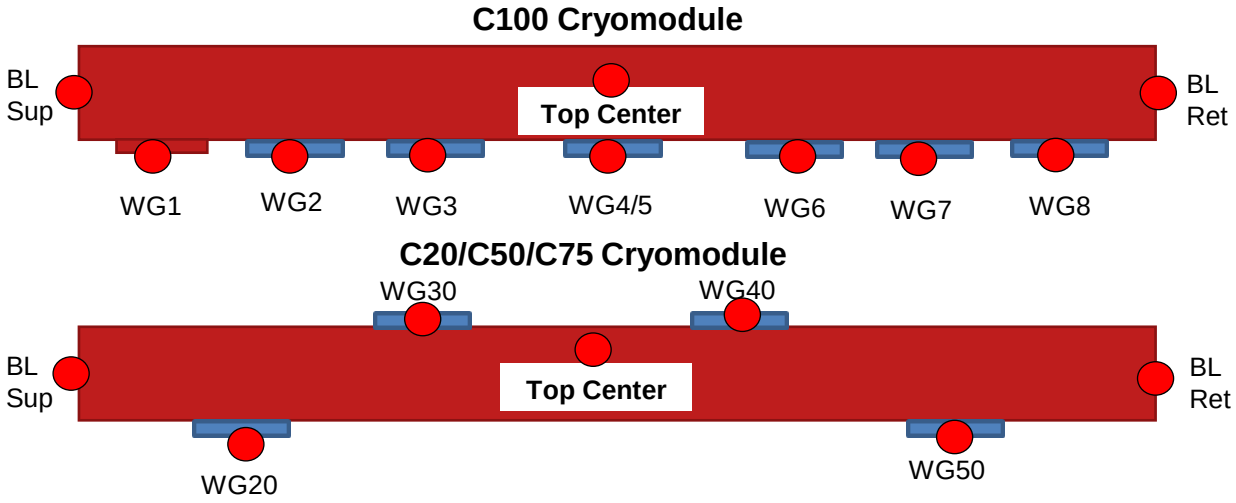
- **Original warm beamline sectors**
  - vacuum pumps
    - non-shielded 100% titanium ion pumps
  - initial 1990's installation insufficient-by-today's-standard cleanliness,
    - however, beamlines were baked-out
    - bake-out stopped after observing Viton gate valve degradation (see later)
  - excessive closure of beamline gate valves for safety reasons,
    - any time somebody entered the tunnel
    - when vacuum pressure excursion above pre-set limit



CEBAF Radiation Monitoring

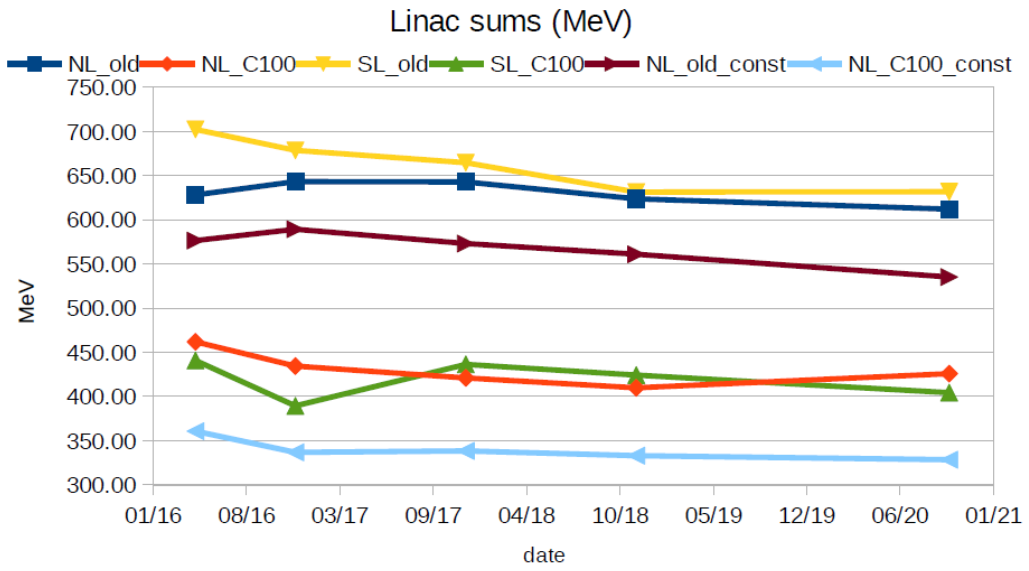
- **Gamma and neutron monitors**
  - installed at warm beamlines in between cryomodules
  - to identify field emitting cavities,
    - but not sensitive enough for field emission onset measurement
  - to optimize gradients to obtain relative minimum neutron dose
- **Geiger-Műller counters**
  - used during commissioning
  - sensors do not survive high radiation environment when energized
    - placed at fundamental power couplers (WG) and on beam-pipe (BL)
  - 100 mR/h radiation limit per cavity
    - operations frequently need to push cavities to reach required energy
      - pushes into neutron emission until 1 R/h per 1 MV/m equivalent trade-off
    - C100 and C75 field emission onset remeasured before annual maintenance periods

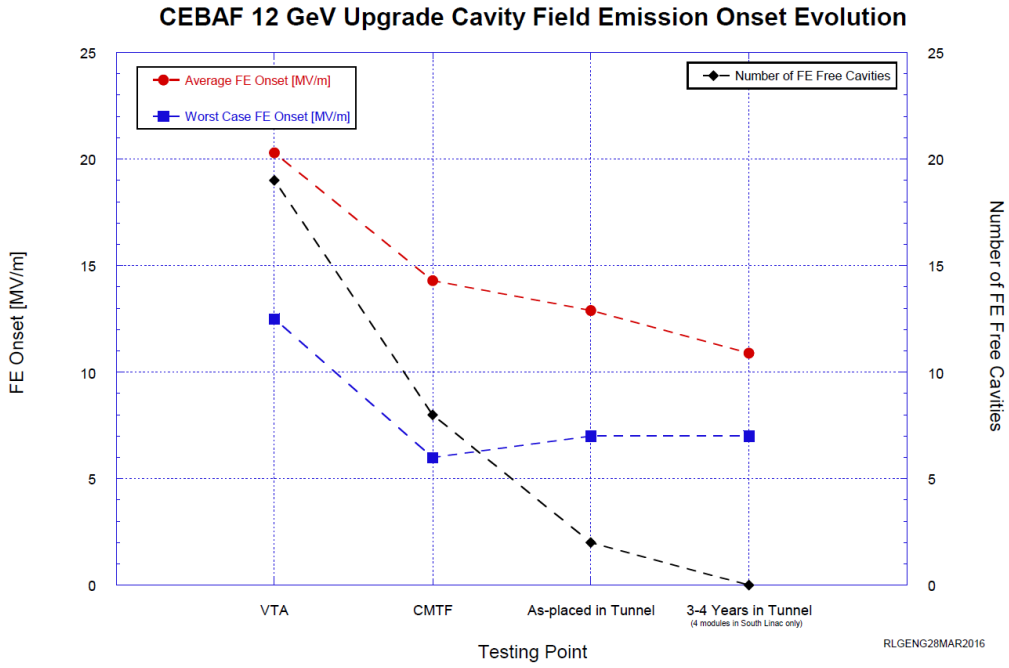




CEBAF Observed Gradient Degradation

- **Observed degradation loss is ~34 to 38 MeV/year**
  - due to worsening field emission and arcing
  - includes losses observed after planned/unplanned thermal cycling
- **Observed degradation rates seem constant**
  - values are used in planning estimates for gradient needs and cryomodule refurbishment
- After a year of operation there was very little degradation in FE onset and operating gradients for C100 cryomodules that were in situ plasma processed in 2023
  - a power fluctuation on the LO power resulted in 3 cavities developing field emitters due to power level spike. Upgraded FCC firmware now protects against such events.
- Data is being gathered on C75 cavities, but results are not yet statistically significant





Suspected Causes for Cryomodule Degradation

See talk by Anne-Marie Valente-Feliciano
https://indico.ibs.re.kr/event/846/contributions/7393/

- **Gas load** from
  - cold-to-warm transition and warm beamline sectors
- **Particulate contamination** from
  - initial **assembly** with insufficient-by-today's-standards techniques
    - now corrected with modern particulate free techniques
  - degrading **Viton-seal** on gate valves
    - 2 valves failed, causing 2 or 3 cavities to become inoperable
      - due to high radiation dose and excessive cycling
      - recent study compared particulate from Viton and all-metal valves [1]
  - **ion pumps**
    - pumps may be field emitting or have whiskers of material inside
    - many pumps appear to arc / discharge at regular intervals.
    - several events were pumps ran at excessive current when thermal cycling
    - some pumps have a great deal of noise on vacuum signal, which could be due to corroded connections caused by high humidity
- **Cavity operation** in field emission
  - due to program requirements for energy reach

[1] Mingqi Ge et al., *Particle measurement on all-metal gate valve for CEBAF beamline via laser-based particle counter*, LINAC 2024 THPB080.

Particulate Contamination

See talk by Anne-Marie Valente-Feliciano
https://indico.ibs.re.kr/event/846/contributions/7393/

- Particulate Species Found:
  - Ti/Ta from vacuum ion pumps)
  - carbon, from Viton elastomer in O-rings and seals in gate valves
  - clay (Si, Ca, Al, Na, K, Mg, etc.) [~50um]
  - stainless steel (Fe, Ni, Cr, Si, etc.) [~50um]

- Catalogue of more than 40 species found in survey assembled so far…
- Further amplified by presence of frozen gas species and the gas sharpening of existing emitters / particulates…

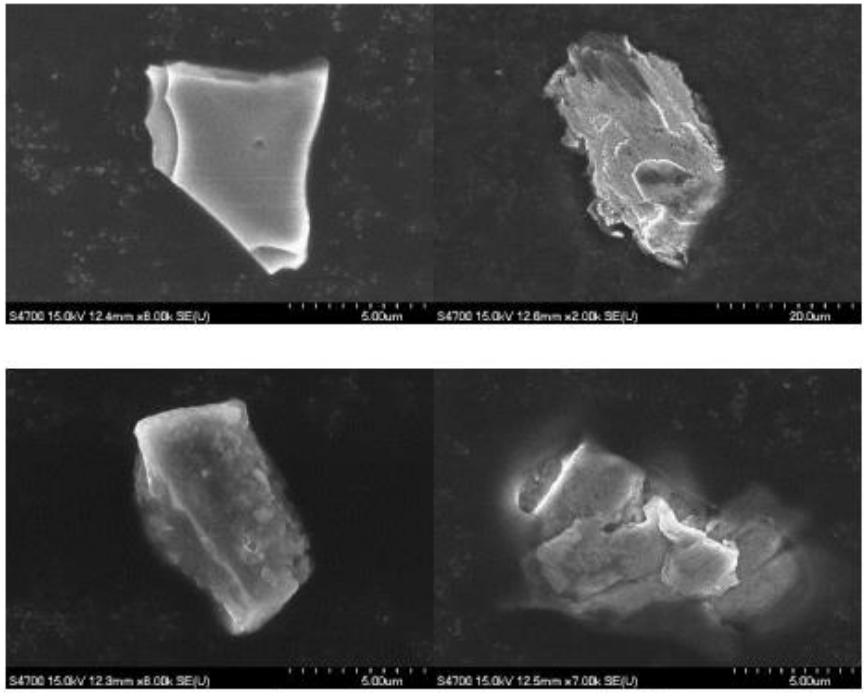


Figure 1: Examples of particulates of Ti/Ta, stainless-steel, air-borne dust aka "clay", and copper (clock-wise starting at upper left), found on the cavity surface of C50-12 before refurbishment.

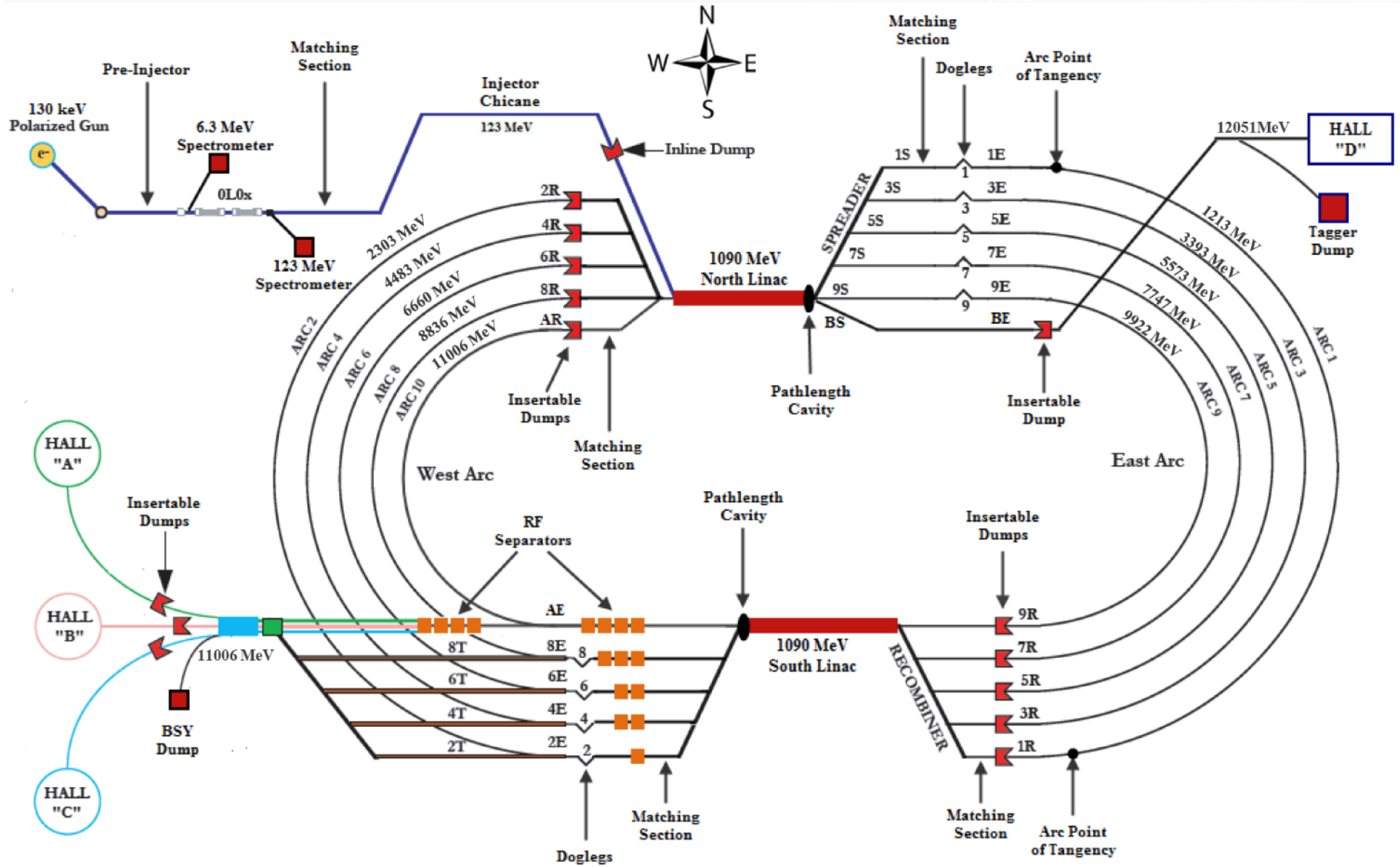
1. R. Geng et al., *Nature and Implication of Found Actual Particulates on the Inner Surface of Cavities in a Full-scale Crymodule Previously Operated with Beam*, Proceedings of SRF2015, MOPB035, JLAB-ACC-15-2198, Whistler, BC, Canada
2. C.E. Reece et al., *Standardized Beamline Particulate Characterization Analysis: Initial Application to CEBAF and LCLS-II Cryomdule Components*, Proceedings of SRF17, TUPB106, JLAB-ACC-17-2620, Lanzhou, China.
3. R. Geng et al., *Understanding and Mitigation of Field Emission in CEBAF SRF Linacs*, Proceedings of IPAC19, WEPRB097, JLAB-ACC-19-2988, Melbourne, Australia.

CEBAF Remediations

- **In situ**
  - helium processing
    - average increase from 2015 campaign was 0.93 MV/m/cavity (2nd processing of most C20s)
  - plasma processing, using He/O_2 mixture
    - average increase from 2023 campaign was 2.7 MV/m/cavity (processing 4 C100s)
    - processed cryomodules degraded 2023 to 2024 by 1.2% in gradient
  - pulse processing
- **Cryomodule refurbishment**
  - annually replace 2 or 3 worst performing cryomodules + girders, complete disassemble and rebuild
  - replace external Viton-sealed gate valves with all-metal gate valves
- **Improved installation and optimized warm beamline sectors**
  - particulate-free installation procedures
  - gate valve interlock specifications revised
    - limit valve closures in transient states & pump restart attempts in adverse conditions
      - increase pressure limits for closing gate valve
      - only close when performing beamline vacuum maintenance or cryomodule replacement
  - specification to NOT high-voltage-pot ion pumps on beamline to avoid particulate sputtering
  - shielded 50% tantalum ion pumps and additional NEG pumps with intermediate all-metal gate valve
  - bake-out of warm beamline sectors, to be combined with ozone cleaning, and venting valve

Backup Slides

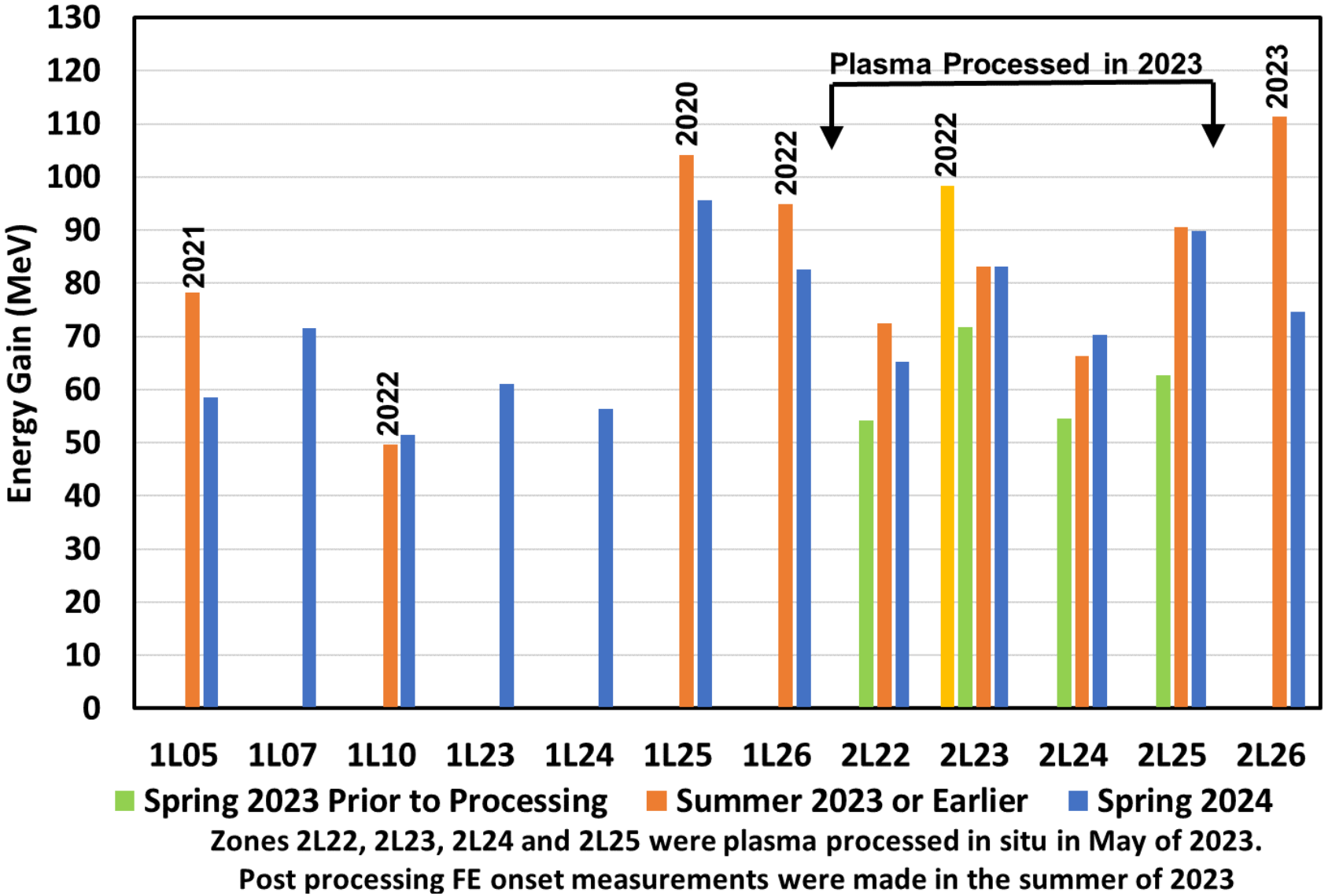
CEBAF 12 GeV Schematics



Vacuum Interlock

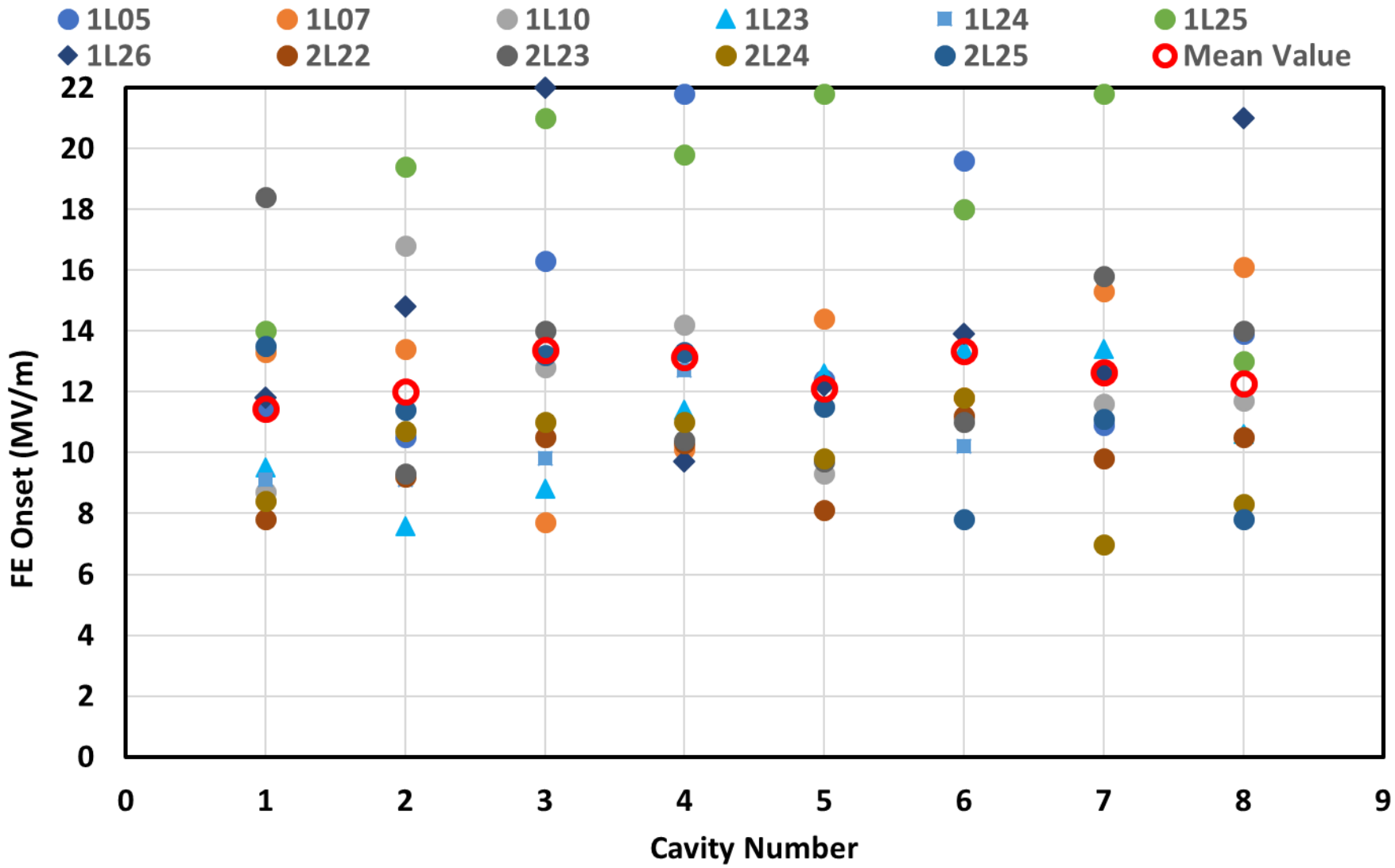
- **Two types of events**
  - transient vacuum excursion caused by outgassing in a cavity
    - gas is either cryo-pumped on to cold surfaces or reaches the nearest ion pump
    - increased vacuum pressure causes gate valve closure
    - elevated risk that particulates generated by the valve action will reach cavity surfaces
  - non-transient vacuum excursion caused by outgassing due to increased thermal shield temperature above 50K
    - increased beamline pressure may cause ion pumps to trip off due to overheating
    - pumps will attempt to restart after cooldown and may cycle multiple times
    - each cycle elevates the risk of particulate contamination
- **Remedies**
  - increased interlock settings, programmable in modern LLRF zones (C75, C100)
    - slow trip: 1E-7 torr >60min.: turn off RF, close valve after few seconds
    - fast trip: 1E-6 torr >3sec.: turn off RF, close valve after few seconds
    - valve trip: 5E-5 torr: close valve, turn off pump after few seconds
  - excursions less than 2 s not exceeding 1E-4 Torr in C100 zones ignored starting fall of 2022

Energy gain at FE onset spring of 2024 compared to previous data



- Cryomodules 2L22, 2L23, 2L24 and 2L25 were plasma processed in May 2023.
- Post processing FE onset data were taken in Aug. 2023.
- The data for 1L05, 1L10, 1L25, 1L26, 2L23, and 2L26 were taken when the cryomodules were commissioned in the indicated years.
- Data were taken for all of the cryomodules shown in the spring of 2024 in preparation for plasma processing in the summer of 2024.
- The cryomodules that were plasma processed degraded from 312 MeV to 308 MeV after 9 months of operation.

FE onset based on cavity number in cryomodule
All data was taken after the cryomodules were in the machine for at least 6 months and prior to plasma processing.



- Data taken in the spring of 2024 towards the end of a run.
- No strong correlation to position in the cryomodule.

Zone	Year Installed
1L05*	2021
1L07R	2021
1L10*	2022
1L23R	2018
1L24	2013
1L25R	2019
1L26R	2023
2L22	2012
2L23R	2022
2L24	2011
2L25	2012

R-rebuilt prior to install
*C75 cryomodules

Summary on processing techniques

Helium Processing

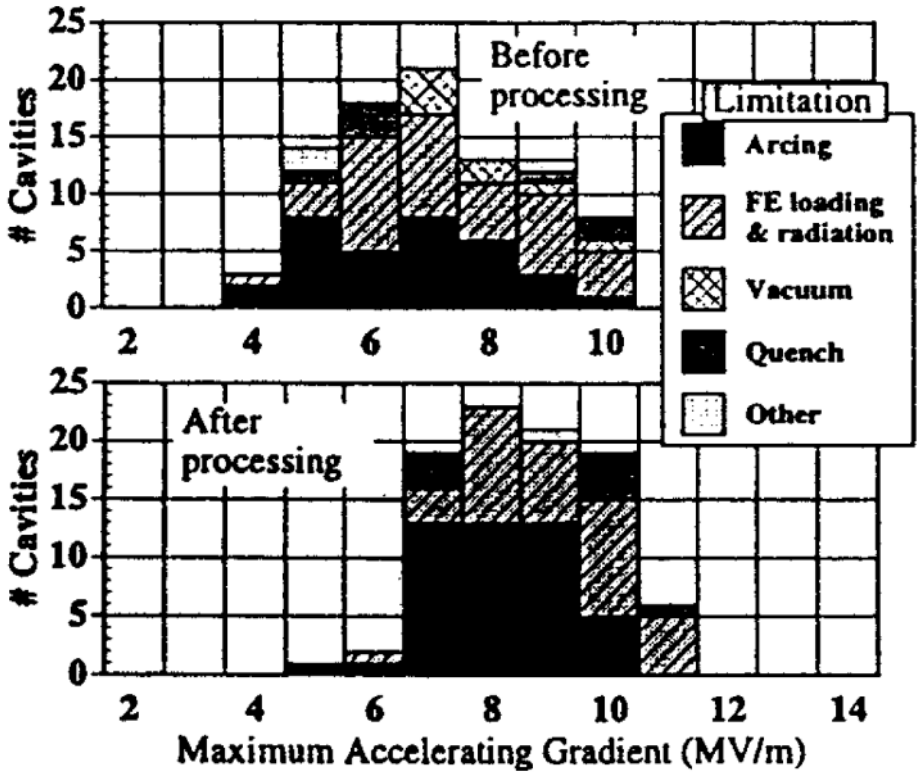
- **Helium processing of cryomodules in the CEBAF accelerator is a well established process, from time to time we will do it on individual cryomodules as it can be done in about 4 days.**
- **We did three major efforts to helium process multiple cryomodules the first was in 1997, the most recent was in 2015.**
- **The 1997 work included pulse processing the waveguide couplers.**
- **In 1996 the average operational improvement was 1.4 MV/m.**
- **In 2015 the average improvement in field emission onset was 0.93 MV/m.**
- **Helium processing did not work well in C100 cryomodules, which seemed to develop new field emitters while we were processing the cavities.**

Plasma Processing

- **We have a well established process for plasma processing C100 cavities and C75 cryomodule**
- **In 2022 and 2023 we processed 44 cavities in cryomodules with an average improvement in field emission onset of 2.7 MV/m.**
- **It is a time consuming process (even doing one cryomodule would take 3 weeks) because the cryomodules must be cycled to room temperature.**
- **We are processed up to five C100 cryomodules in the summer and early fall, the results is not available yet.**

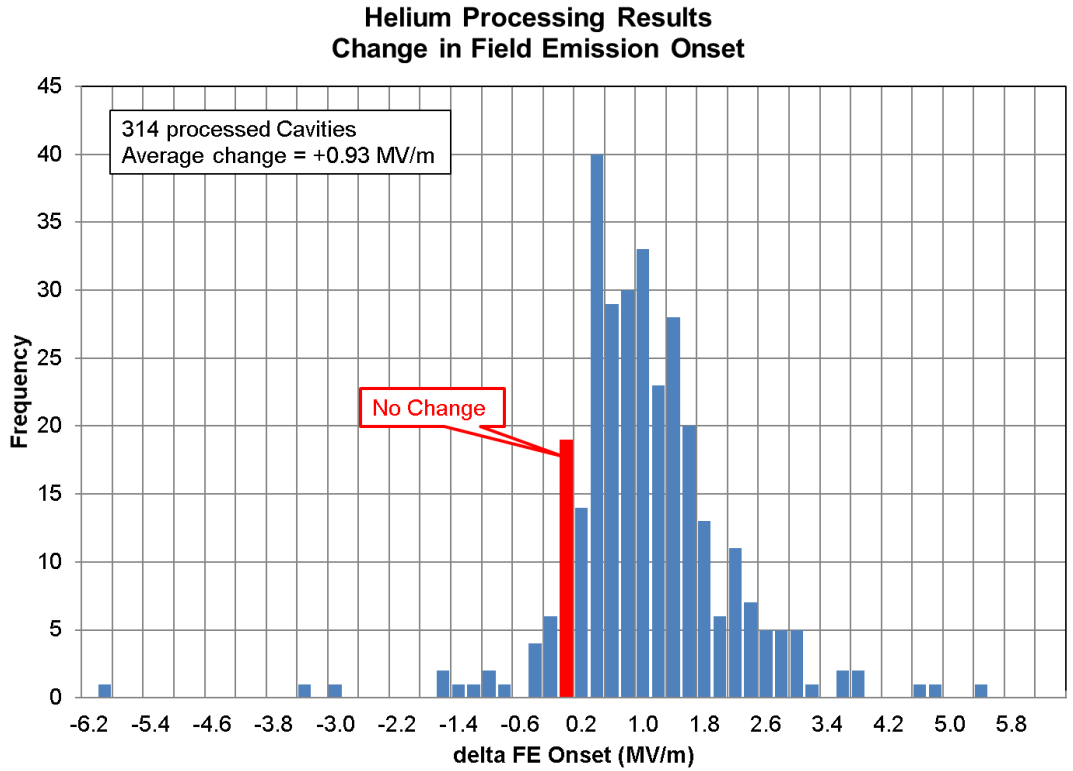
Helium processing in CEBAF

- 1997 helium processing report [1]
- 90 cavities in 12 cryomodules were processed
- We also pulsed processed the fundamental power coupler vacuum space on 10 cryomodules.
- Net gain was 63 MeV or an average of 1.4 MV/m



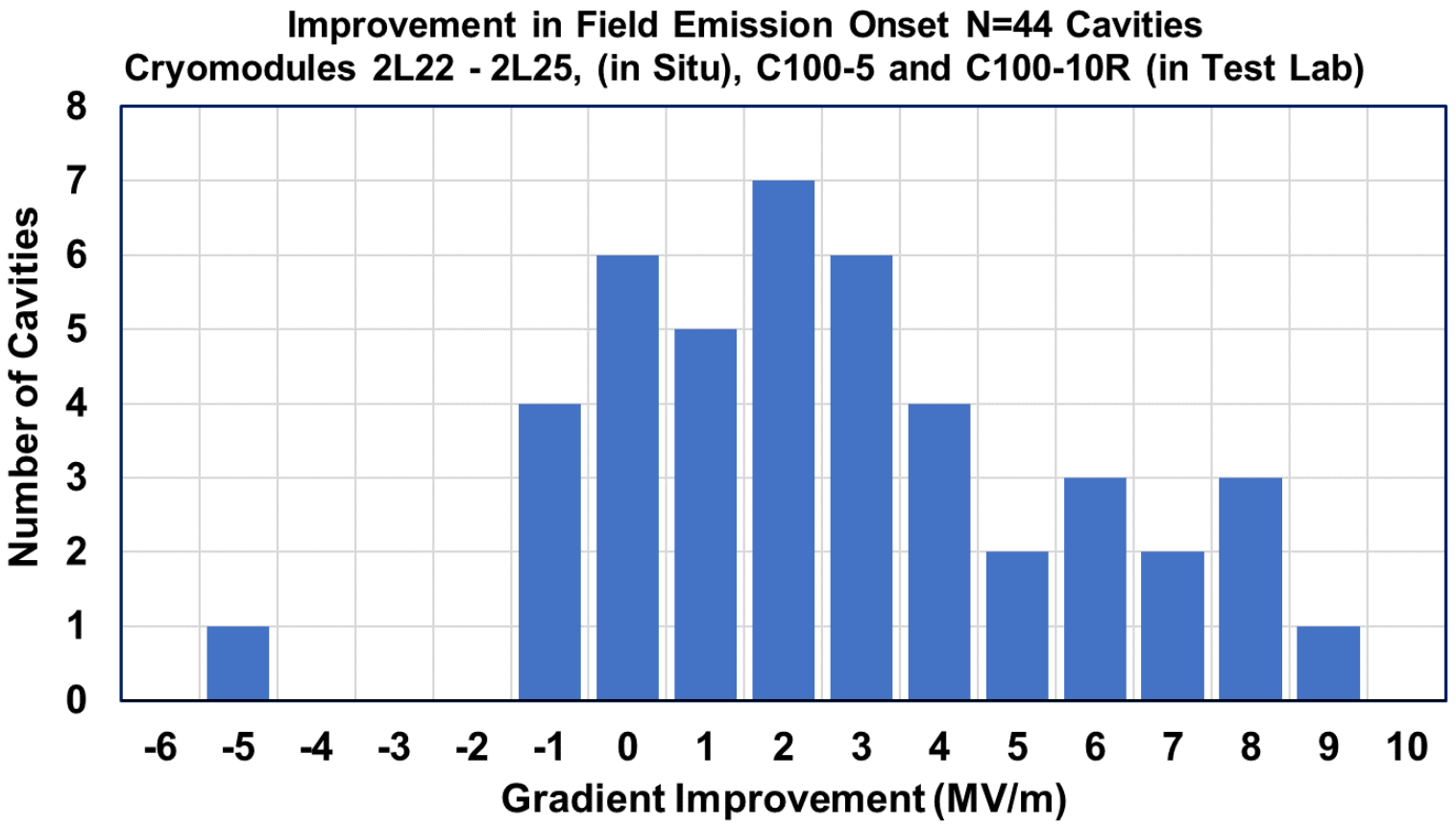
[2] Reece, et. al., Improvement of the operational performance of SRF cavities via in situ helium processing and waveguide vacuum processing, PAC 1997

- 2015 helium processing report [2]
- 314 cavities in 45 cryomodules were processed
- Net gain was 201 MeV with an average increase in field emission onset of 0.93 MV/m
- Only a fraction of the C100 cryomodules were processed because a number of the cavities degraded when processed.



[2] Drury, et. al., Results of the 2015 helium processing of CEBAF cryomodules, NAPAC 2016

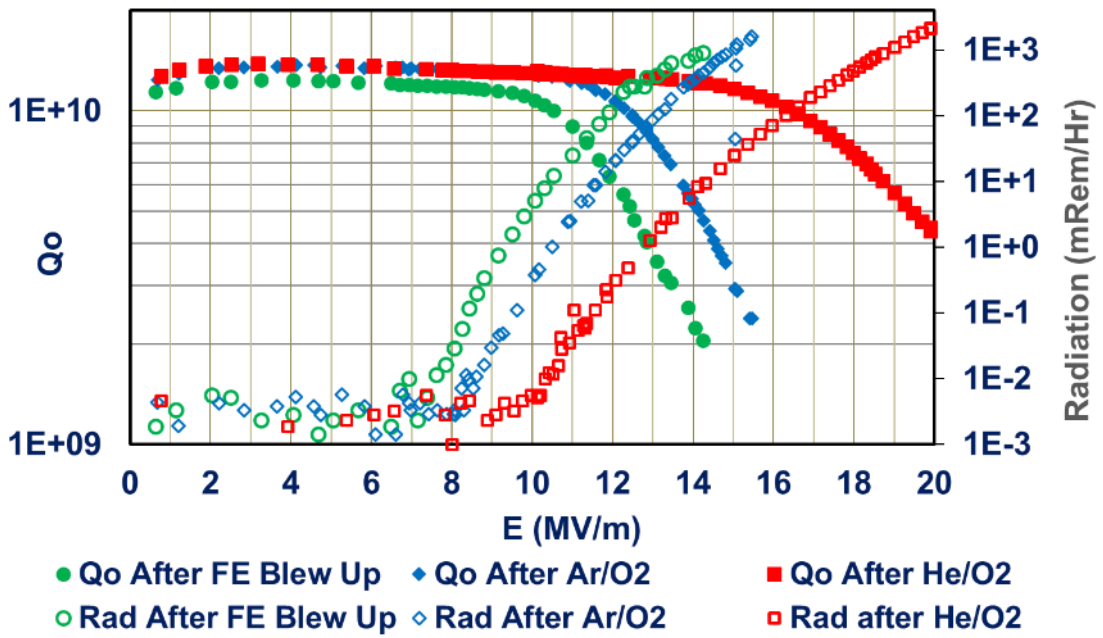
Improvement in field emission after plasma processing



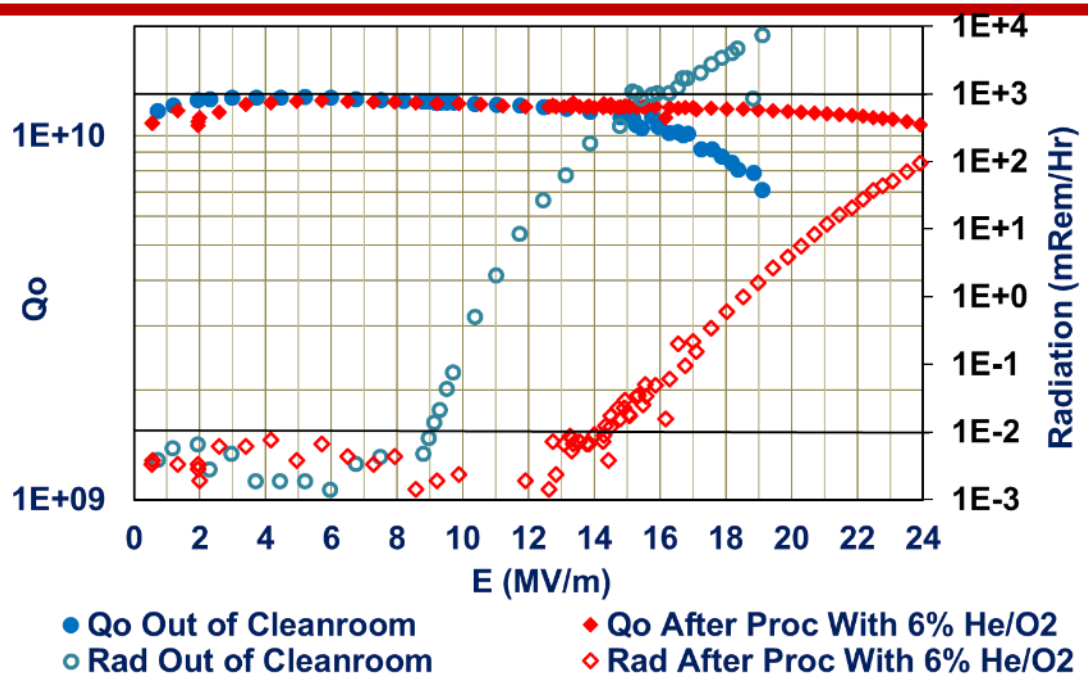
- Average improvement in field emission onset was 2.7 MV/m.
- 40 of the 44 cavities that were processed were in cryomodules that also had their beam line gate valves replaced.
- The 4 cryomodules processed in-situ had a 59 MeV improvement in FE onset.
- 6 of the 44 cavities went from field emitting to field emission free after processing

	FE Free Before (MeV)	FE Free After (MeV)	Delta (MeV)
C100-5	59.7	71.5	11.8
C100-10R	95.6	105.4	9.8
2L22	54.2	65.3	11.1
2L23	71.8	86.6	14.8
2L24	54.6	72.3	17.7
2L25	62.7	78.2	15.5

VTA results that resulted in us changing from argon/oxygen to helium/oxygen



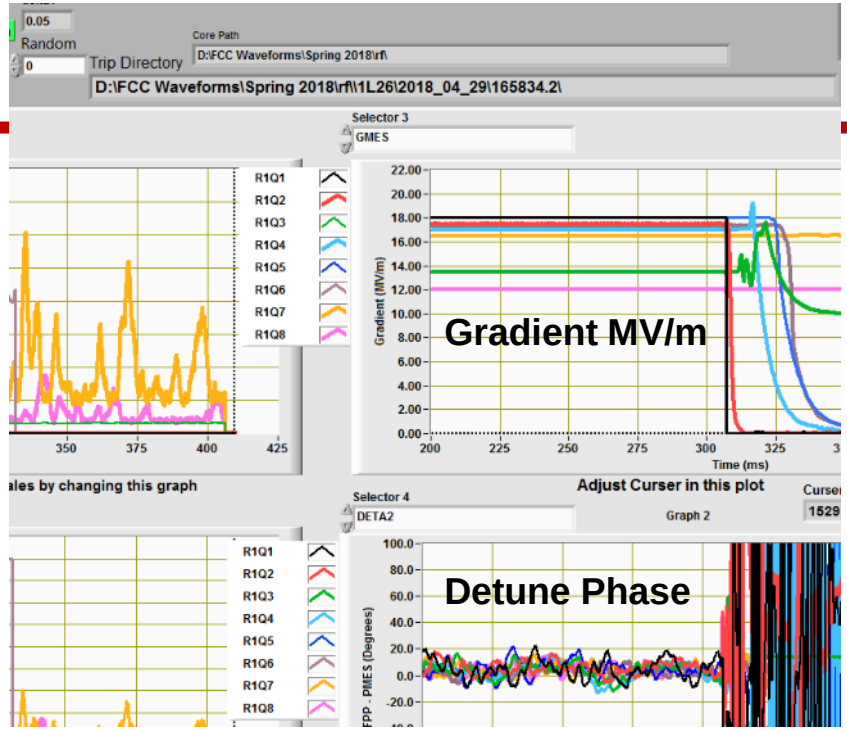
- After a series of experiments we decided on a protocol of processing with 1% oxygen/argon followed by 20% oxygen/argon.
- About a year later we started experimenting with helium/oxygen.
- We processed a blown up field emitter using argon/oxygen then processed it with 2% oxygen/helium and got an additional 2 MV/m improvement.

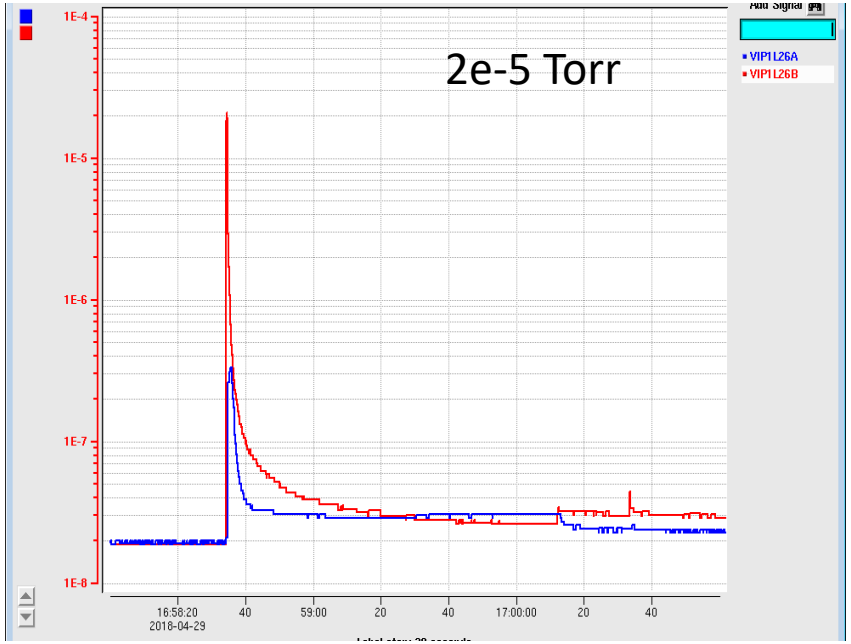


- We followed that with a series of experiments with different gas mixtures of helium and oxygen at different pressures and oxygen percentages
- Out of clean room (blue) Process twice with 6% oxygen 94% helium (Red)
- Demonstrated that helium/oxygen is an effective gas mixture.

Fast “Electronic Quench”

- Fall time of cavity gradient faster than 50 us (one point at this acquisition rate).
- Cavity seemed to be operating normally up until this point.
- Theory -- vacuum burst in cavity releases large quantities of electrons which absorb the energy within the cavity.
- 93% of the fast quenches in the Fall 2018 run were in cavities 1 or 8 the rest were distributed between the other 6.
- Extensive leak checking was done without finding a problem. FE radiation induced photo-desorbtion is likely.





- Corresponding beamline vacuum excursion.
- Red trace is pump next to cavity 1 blue trace is at the upstream end of the girder.
- Peak vacuum signal adjacent to cavity 2e-5 Torr at the other end of the girder was 3e-7 Torr.
- No events were recorded where cavity 1 in one zone and cavity 8 in the adjacent zone had the same fault at the same time which indicates that the event was not due to a vacuum burst in the girder between the cryomodules.

Jefferson Lab