Field Emission in Superconducting Accelerators:

Instrumented Measurements for Its Understanding and Mitigation

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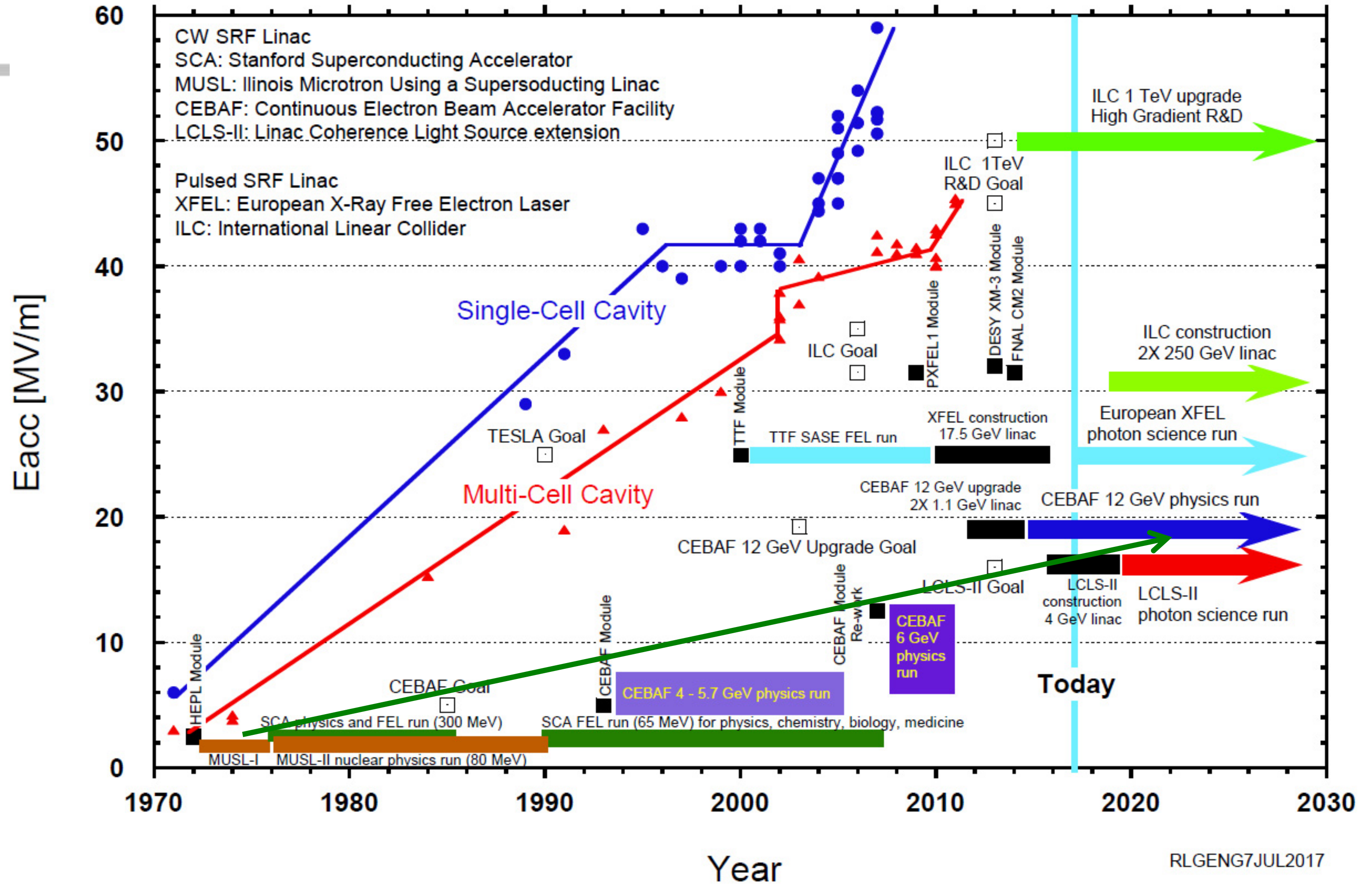
Invited Talk at IBIC17

Outline

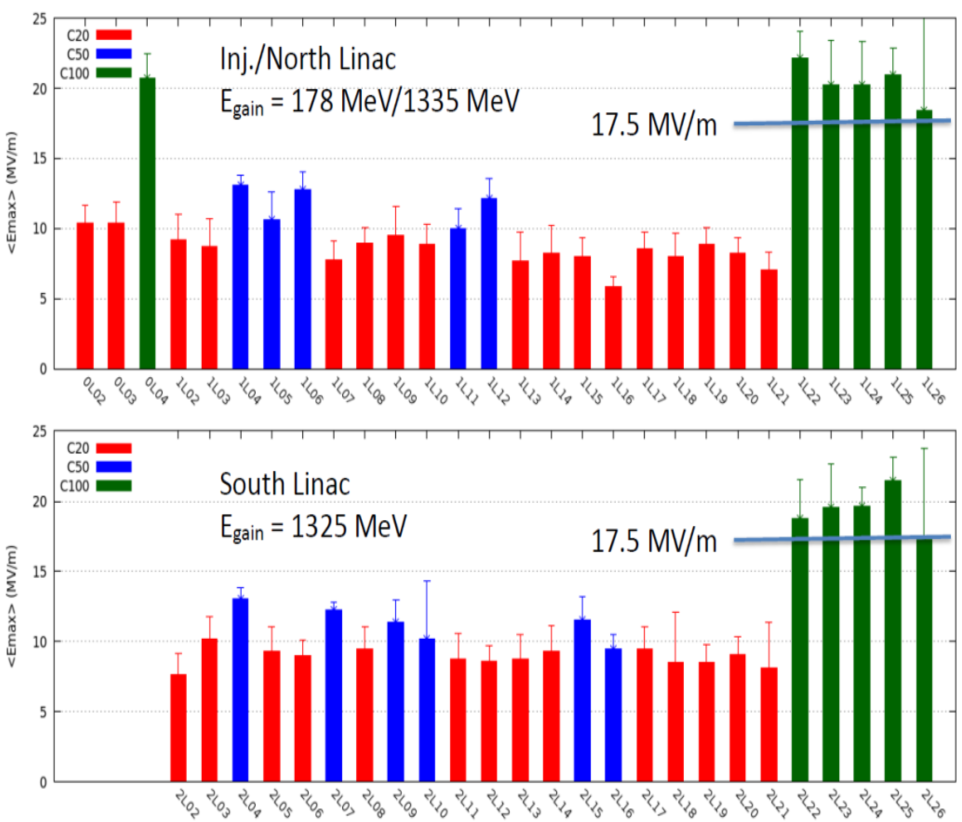
- Introduction
- FE basics including FE instrumentation in SRF cavity or cryomodule testing
- FE in SRF accelerator with a focus on instrumented measurements at CEBAF
- Conclusion

L-band SRF Linear Accelerator Technology and Impact to Nuclear, Elementary Particle, and Photon Sciences



- New accelerator projects adopting SRF technology
- FE an issue of interest: cavity gradient capability -> accelerator operation: Beam energy; reliability
- Amazing progress in SRF gradients, past success overcoming FE in Single-cell cavity, Multi-cell cavity
- High gradient SRF accelerator operation free from FE – one of the greatest remaining challenge

12 GeV CEBAF Challenge & Opportunity

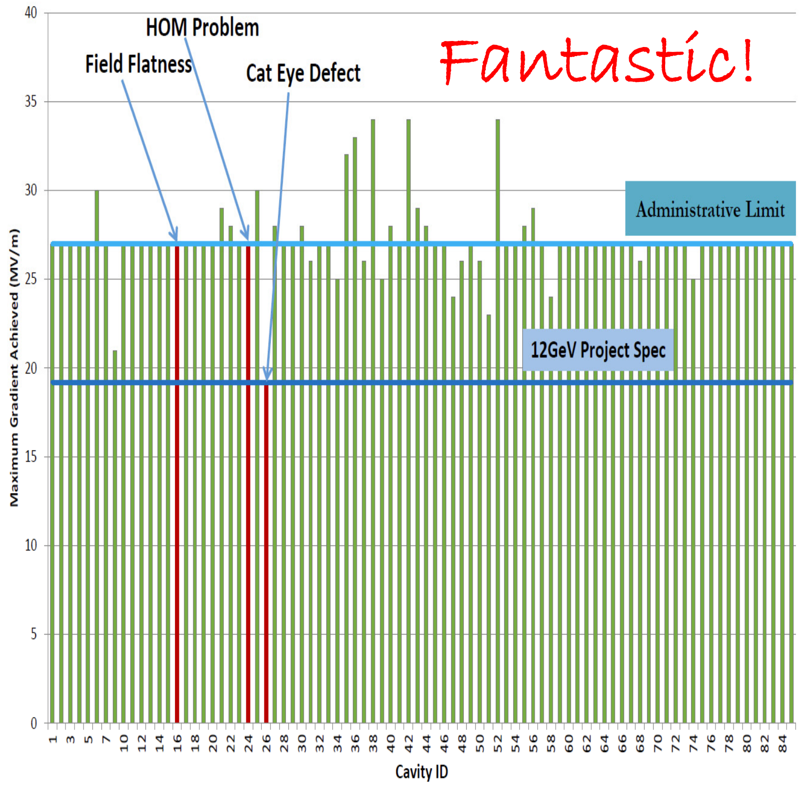


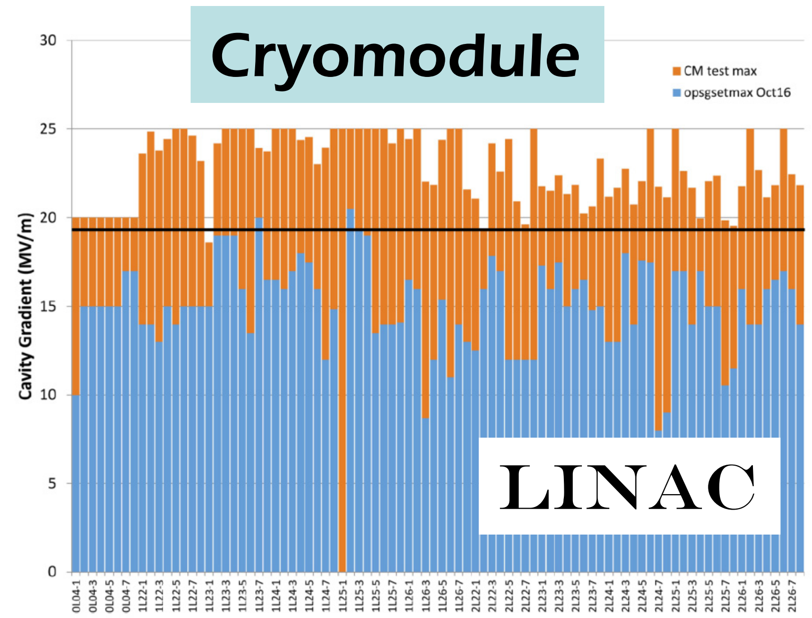
C20: original CEBAF 5-cell cavities
C50: refurbished C20 cavities
C100: New 7-cell cavities

- CEBAF fresh upgrade 6 GeV to 12 Gev enabled by adding 80 new SRF cavities
  - Specification CW operation at gradient 17.5MV/m, cavity qualification gradient 19.2MV/m **Unprecedented**
- Two 1.1 GeV CW SRF linacs
- 418 cavities in 52.25 cryomodules
- 3 years of beam operation since 2014
  - CEBAF at forefront in addressing a great SRF challenge

What is the Problem?

Final qualification ***individual cavity***





- Why can't cavities run in linacs at gradients as in cryomodules?
- Root causes being studied: FE a principal issue of interest

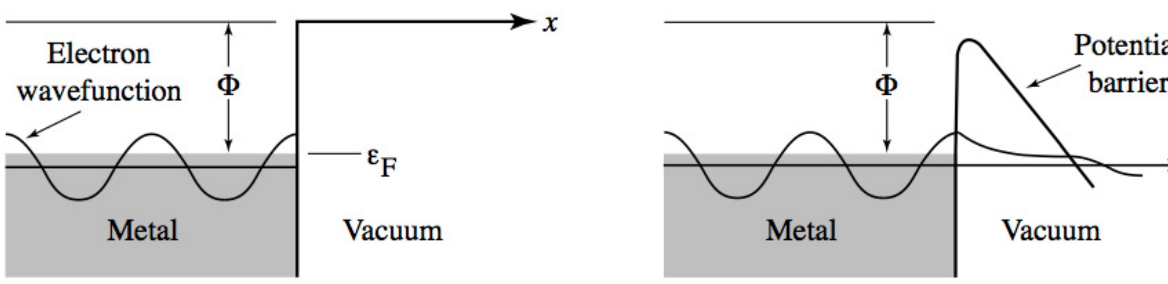
Field Emission Basics – Theory

- Electron emission from site of "field emitter"
  - Quantum mechanical process – tunneling effect
  - Fowler-Nordheim Law: note exponential field dependence of tuneling current

$$I_{FN} = j_{FN} A_{FN} = A_{FN} \frac{e^3 E^2}{8\pi h \Phi t^2(y)} \exp\left(-\frac{8\pi\sqrt{2m_e\Phi^3}v(y)}{3heE}\right)$$

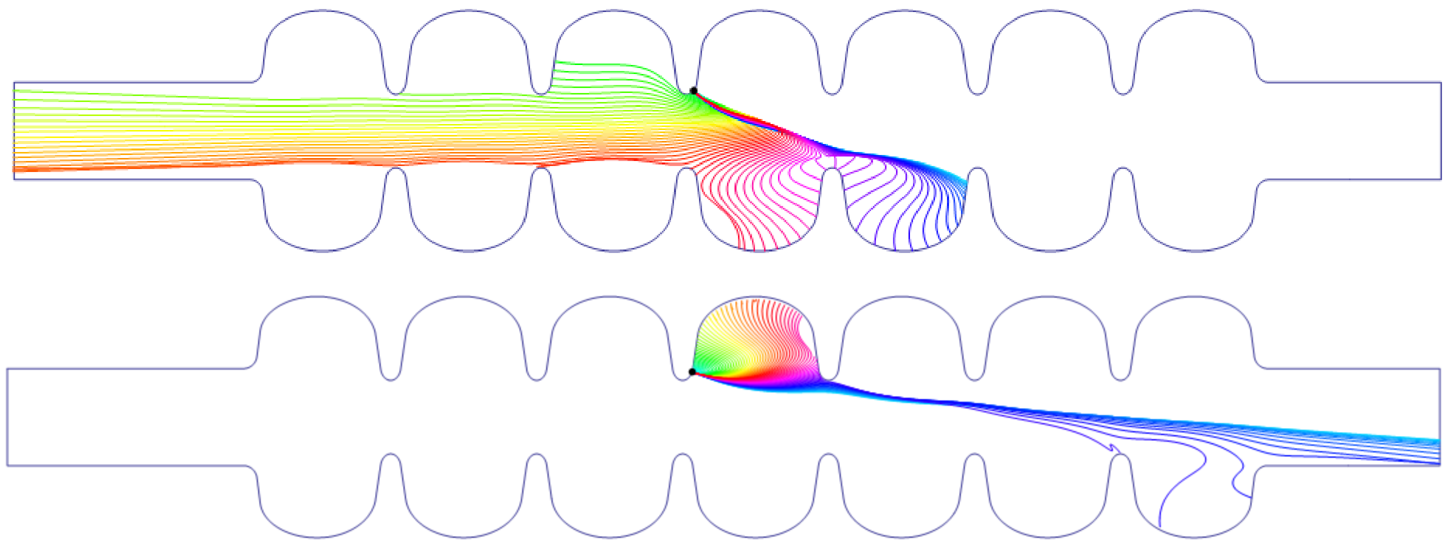
- Modified Fowler-Nordheim
  - Electric field enhancement factor β_{FN}
    - Typical value 50-500 for SRF cavity
  - Effective emitter area A_{FN}
    - Typical value 10^{-18} – 10^{-9} m^2

$$I_{FN} = j_{FN} A_{FN} = A_{FN} \frac{e^3 (\beta_{FN} E)^2}{8\pi h \Phi t^2(y)} \exp\left(-\frac{8\pi\sqrt{2m_e\Phi^3}v(y)}{3he\beta_{FN} E}\right)$$



(a) (b)

FE in SRF Cavities

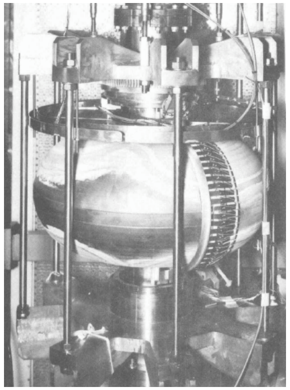


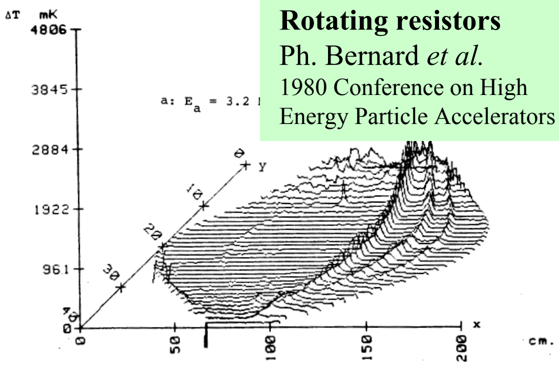
- Electrons emitted from localized site, point-like, sources
- Family of trajectories depending on electron emission phases
  - Trajectory confined in plane defined by cavity axis and emitting site due to symmetry
  - Get lost when hitting cavity wall, or exported out of cavity (forward or backward)
- Electrons get accelerated by gaining energy from EM field in cavity
- Electrons hitting wall: deposit heat, create Bremsstrahlung X-rays

Diagnosis by Instrumentation

FE Instrumentation: Cavities or Cryomodules

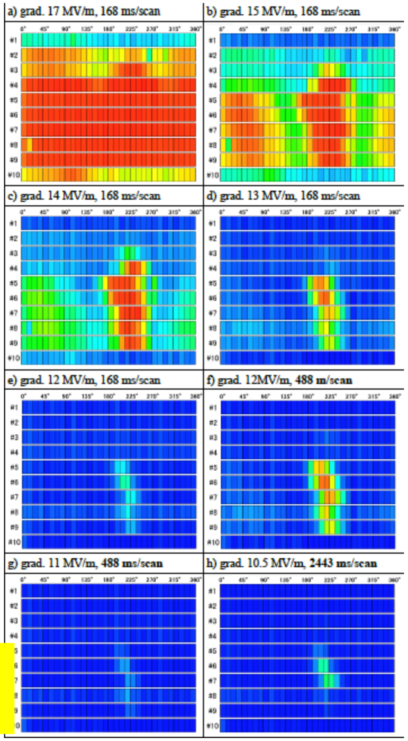
- Temperature mapping w/ array of carbon resistors
- Electron detecting w/ probes
- X-ray monitoring/mapping w/ photodiodes, ionization chamber, NaI scintillator, G-M tubes; At liquid helium or in air; arrays of detectors (rotating or fixed) for X-ray mapping
- X-ray photography w/ "pin hole camera" placed out side dewar



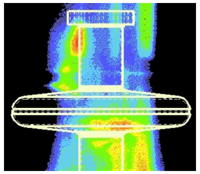


Rotating resistors
Ph. Bernard *et al.*
1980 Conference on High Energy Particle Accelerators

Fixed PIN diodes
H. Tongu et al, IPAC2017

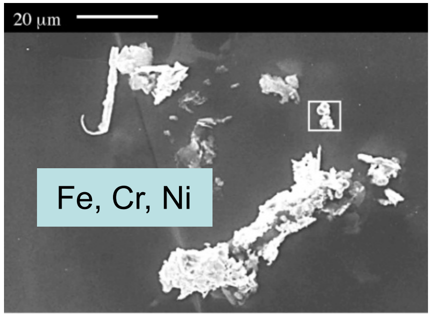


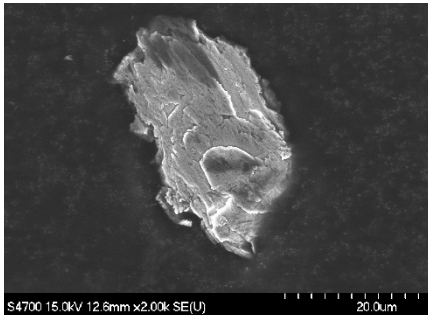
Re-usable X-ray film
T. Grimm et al, SRF2001

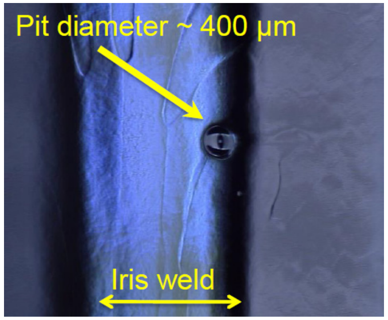


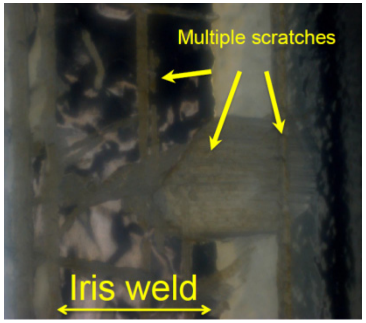
Field Emission Basics – Field Emitter

- Microscopic particles
  - From surface processing
  - Airborne
  - From cavity assembly hardware & tool
- Geometrical defects
  - Is permanent feature, is part of cavity
  - Pits (from fabrication)
  - Scratches







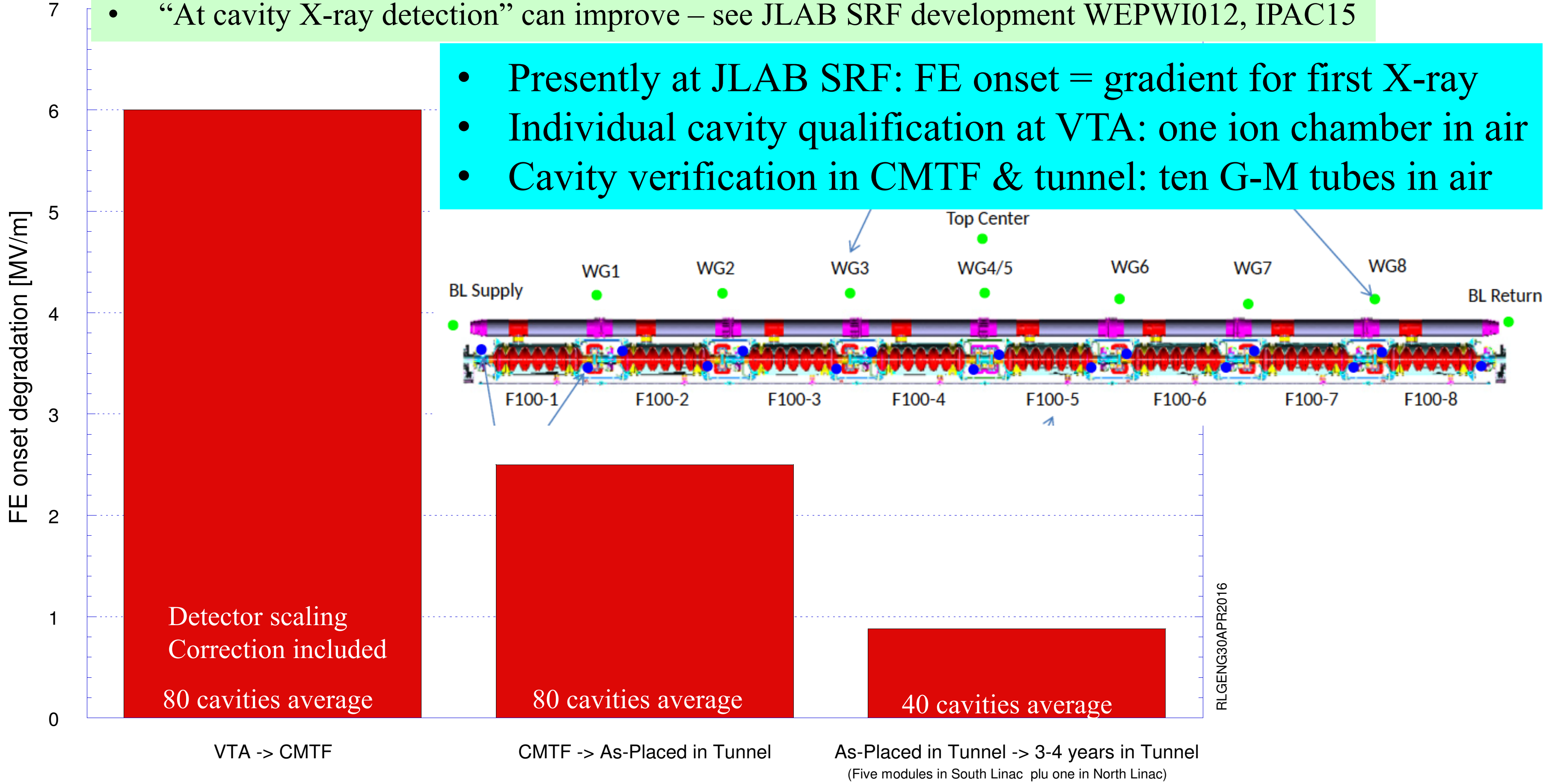


- Cavities FE limited by geometrical defects rejected for repair
- Cavities FE limited by particulates re-cleaned till passing qualification
- Key: Particulate input into cavities passing final qualification

Degradation of FE Onset

- Universal definition of FE onset still lacking
- "At cavity X-ray detection" can improve – see JLAB SRF development WEPWI012, IPAC15

- Presently at JLAB SRF: FE onset = gradient for first X-ray
- Individual cavity qualification at VTA: one ion chamber in air
- Cavity verification in CMTF & tunnel: ten G-M tubes in air



Particulate input sources

Cavity string assembly
- Flange joining
- gasket crashing
- String evacuating

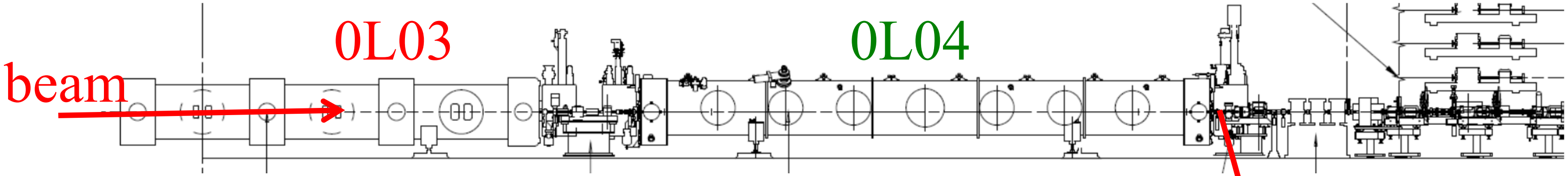
Cryomodule handling
- Shipping
- Ion pump restarting

Components near cryomodule
- Gate valve actuating
- Ion pump restarting
- Gas molecules input (FE enhancement)

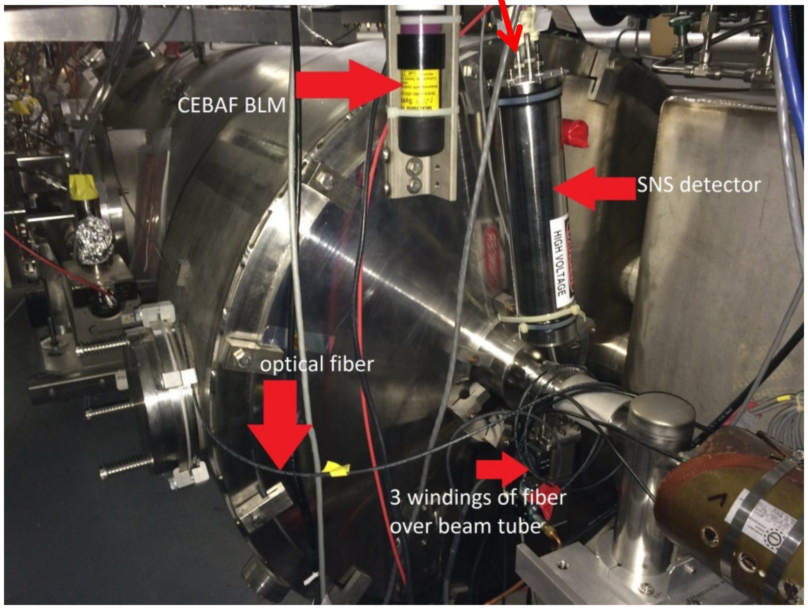
FE in SRF Accelerators

- Impact: energy reach, reliability and maintainability
- Unique aspects
  - FE electrons charging ceramic windows in RF input couplers causing fast trips as was understood for C20 cryomodules
  - FE electrons captured, transmitted into other cryomodules and gain increasingly larger energies, causing radiation damage
  - Continued *gas input* into the cavity due to cryopumping, activate new field emitters or enhance FE of existing field emitters
  - *Particulate input* from cycling of gate valves
  - Competing driving forces for beam energies and reliability. Pushing gradient for higher energies may cost system reliability when FE is present

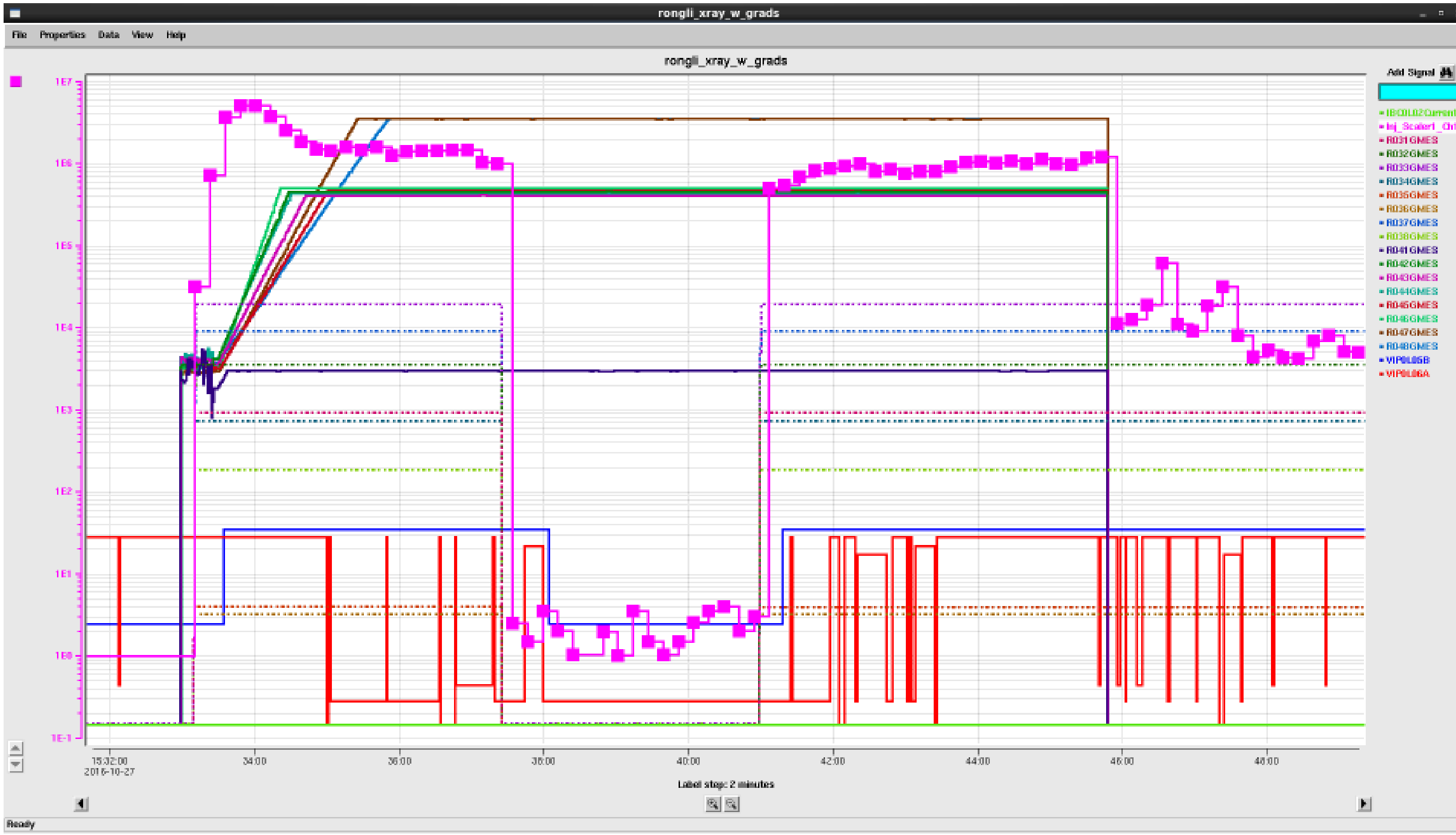
Propagation of FE Electrons – Injector Zones



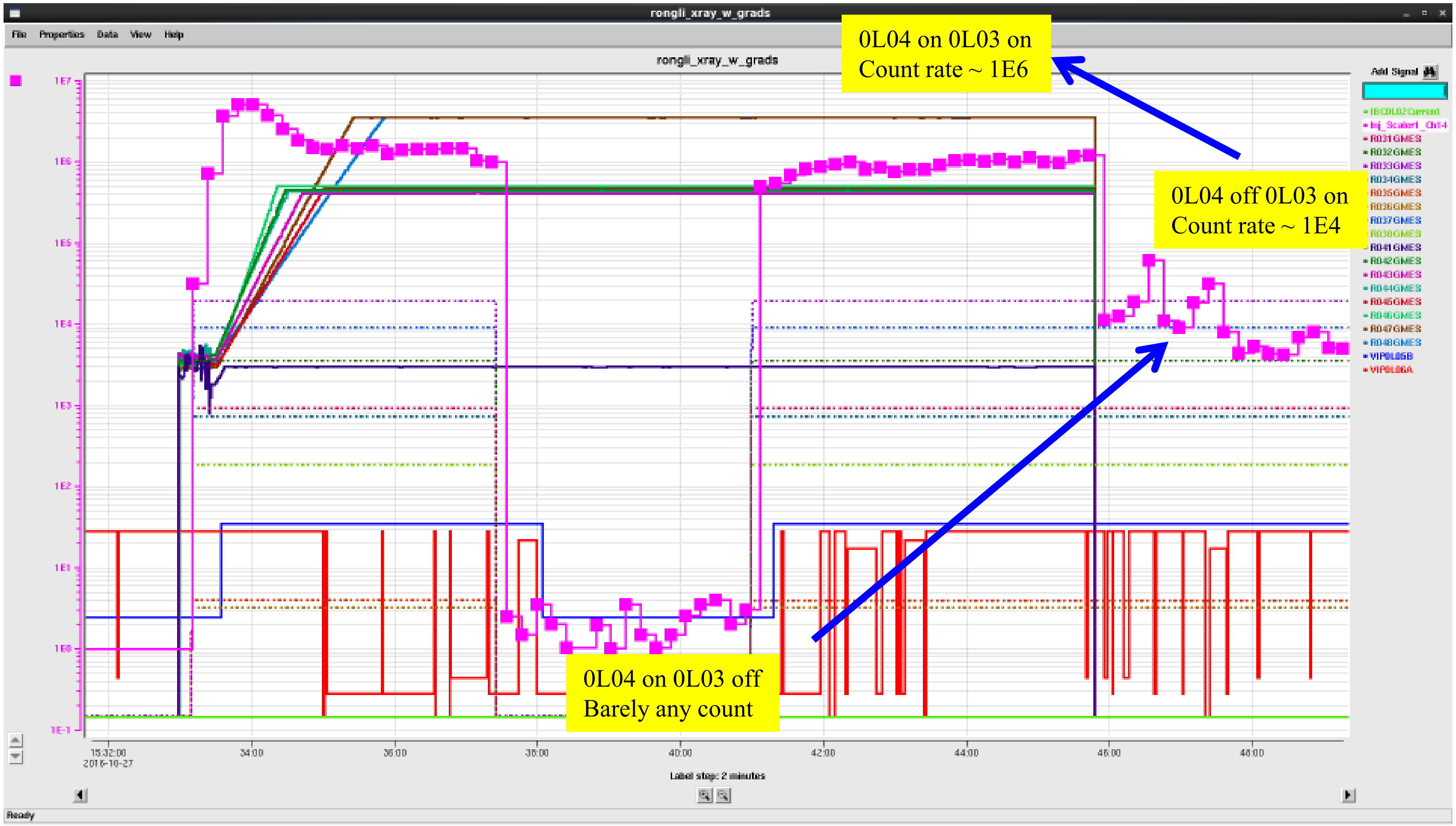
- Several tests were performed in different zones
- Tests done in the injector zones 0L03 (C20) and 0L04 (C100)
- SNS-type fast beam loss monitor (plastic scintillator + PMT) attached to the downstream endplate of cryomodule in zone 0L04.



Radiation Enhancement Effect Observed

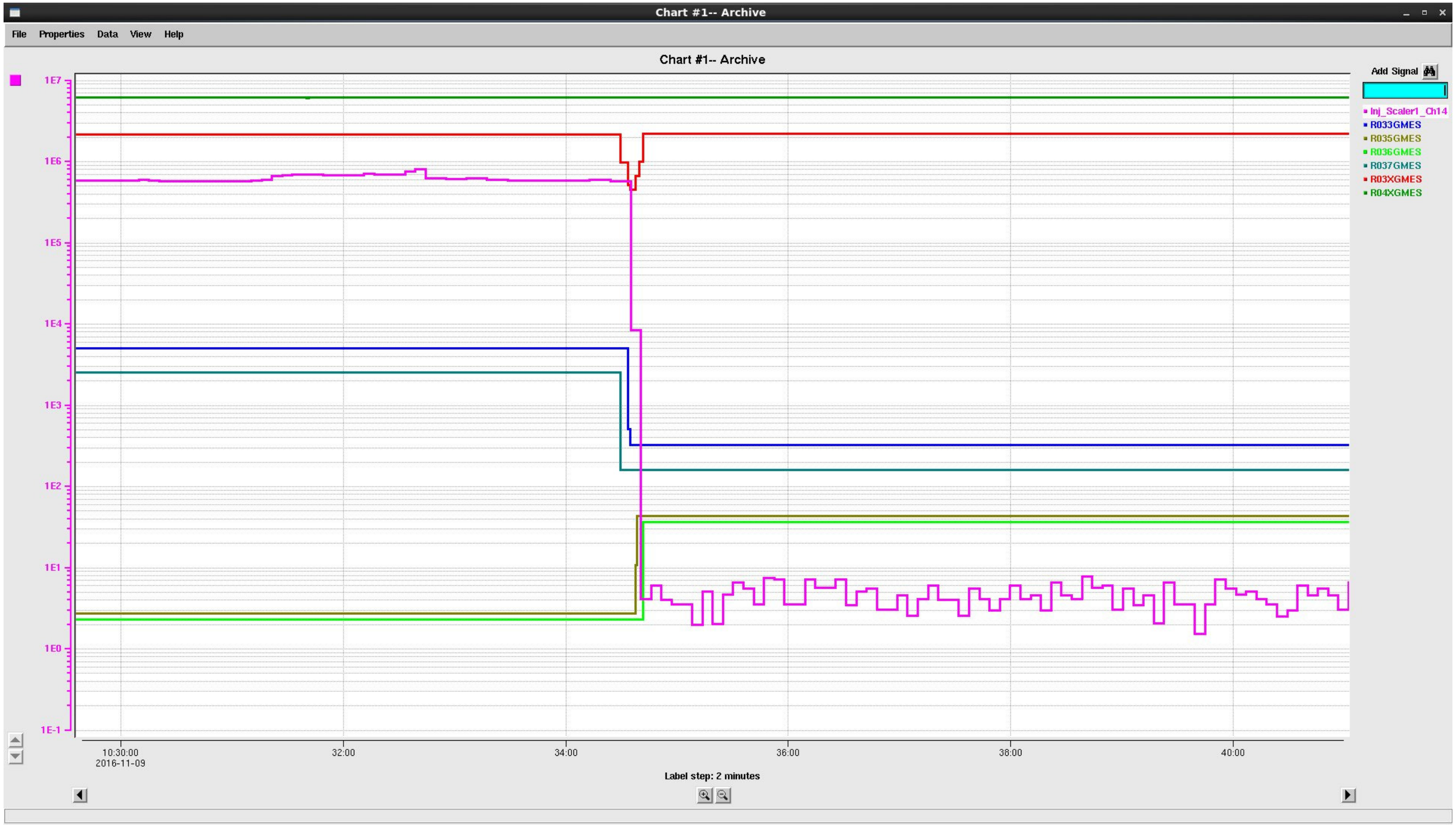


Radiation Enhancement Effect Observed



Radiation Reduction by Gradient Redistribution

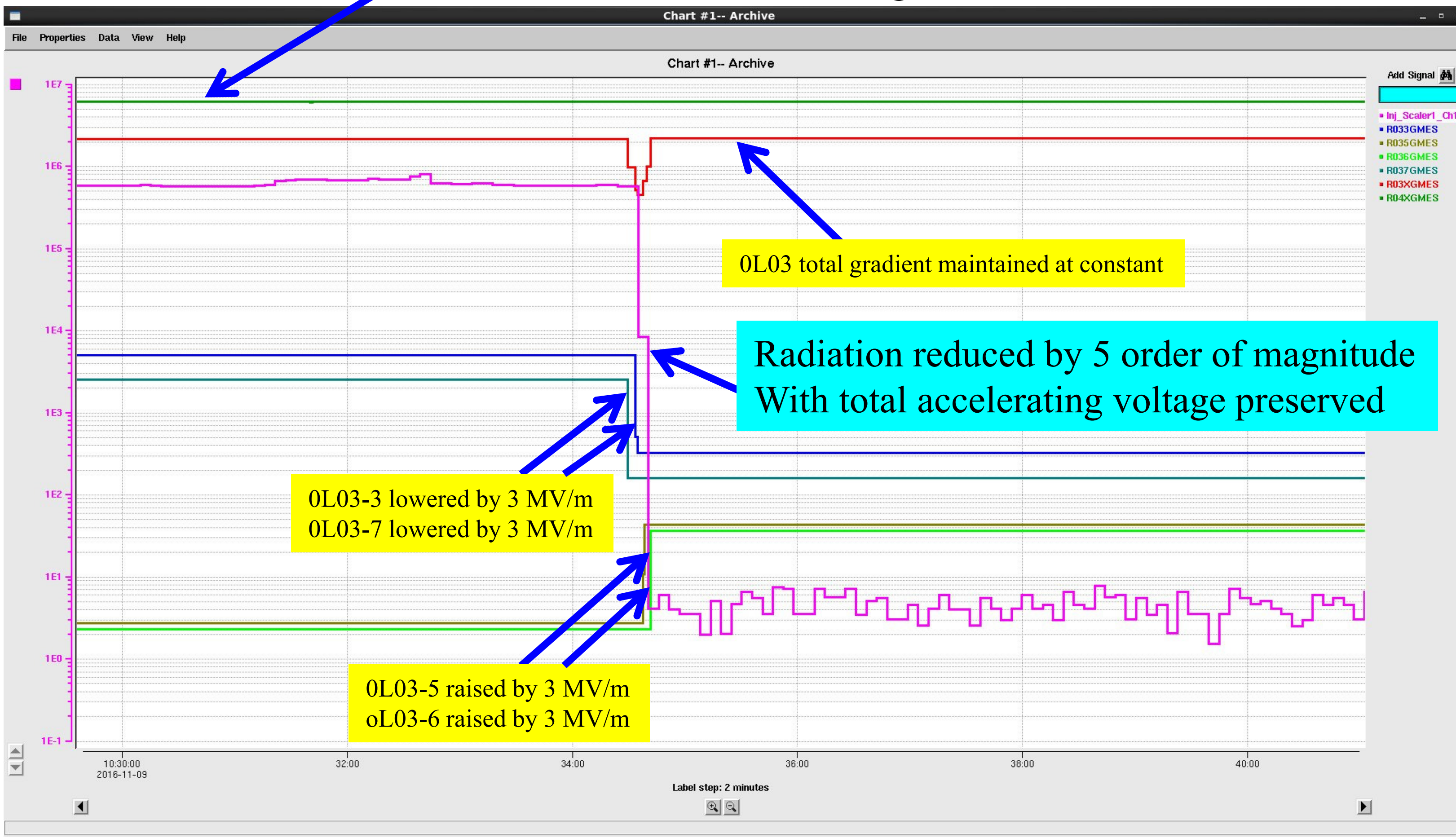
Lower gradient of FE source cavities
Raise gradient of FE free cavities



Radiation Reduction by Gradient Redistribution

Lower gradient of FE source cavities
Raise gradient of FE free cavities

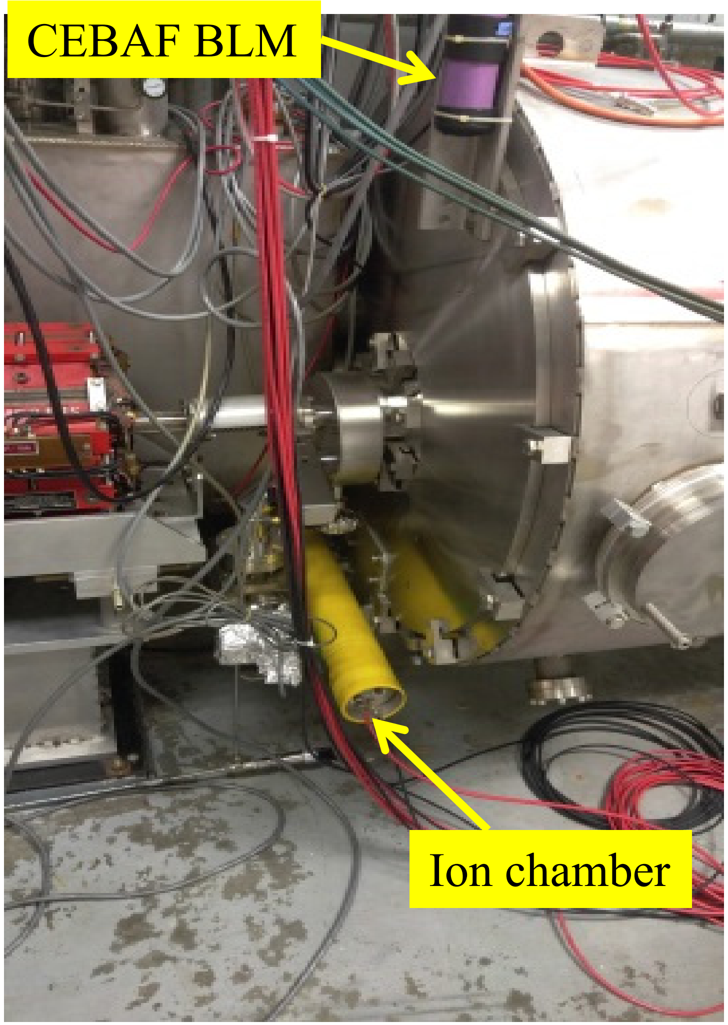
0L04 at constant gradient



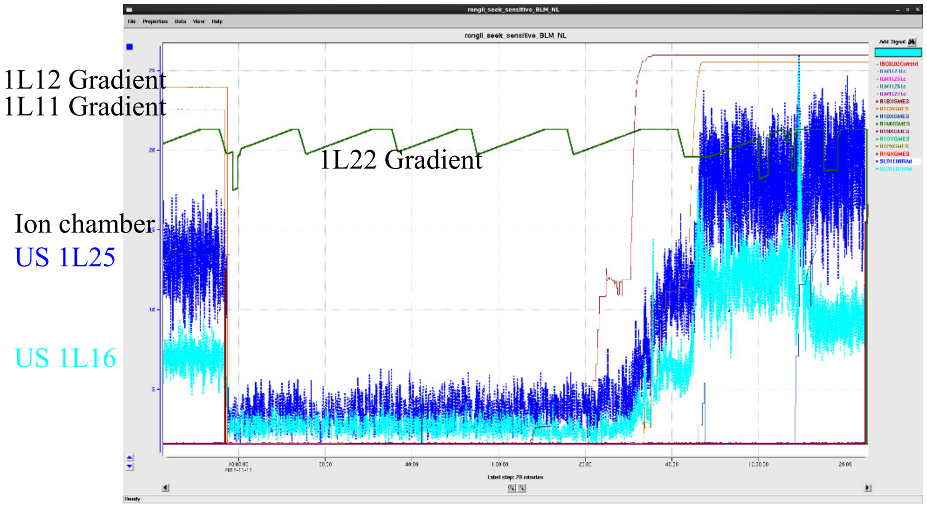
Area monitor γ-probe upstream of 0L03 indicated equally effective radiation reduction there

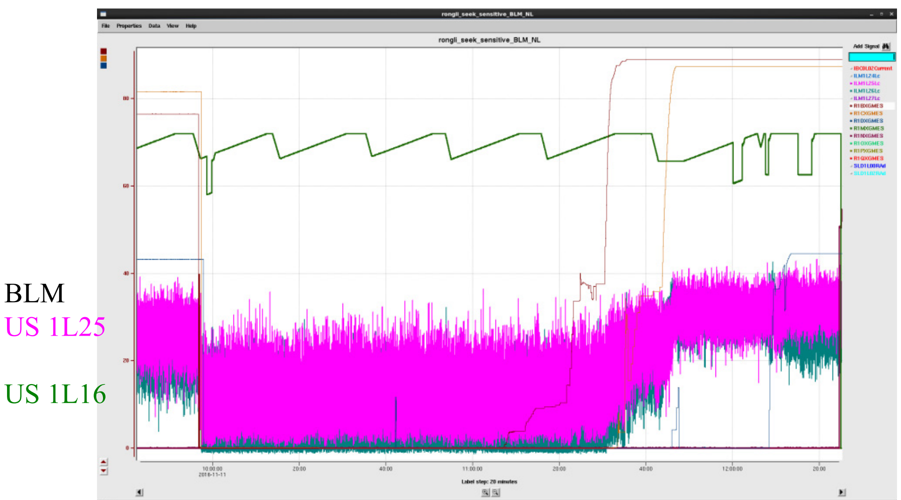
Propagation of FE Electrons – 1GeV Zones

- In Summer 2016, four calibrated high-rad ion chambers placed in 1L25 & 1L26 zones
- FE electrons can be accelerated up & downstream between cryomodules
- Inter-cavity phasing studied
- 3% change in gradient caused 50% change in rad
- Radiation levels produced by the transmitted electrons go as the ratio of their energy



Long Distance Propagation of FE Electrons





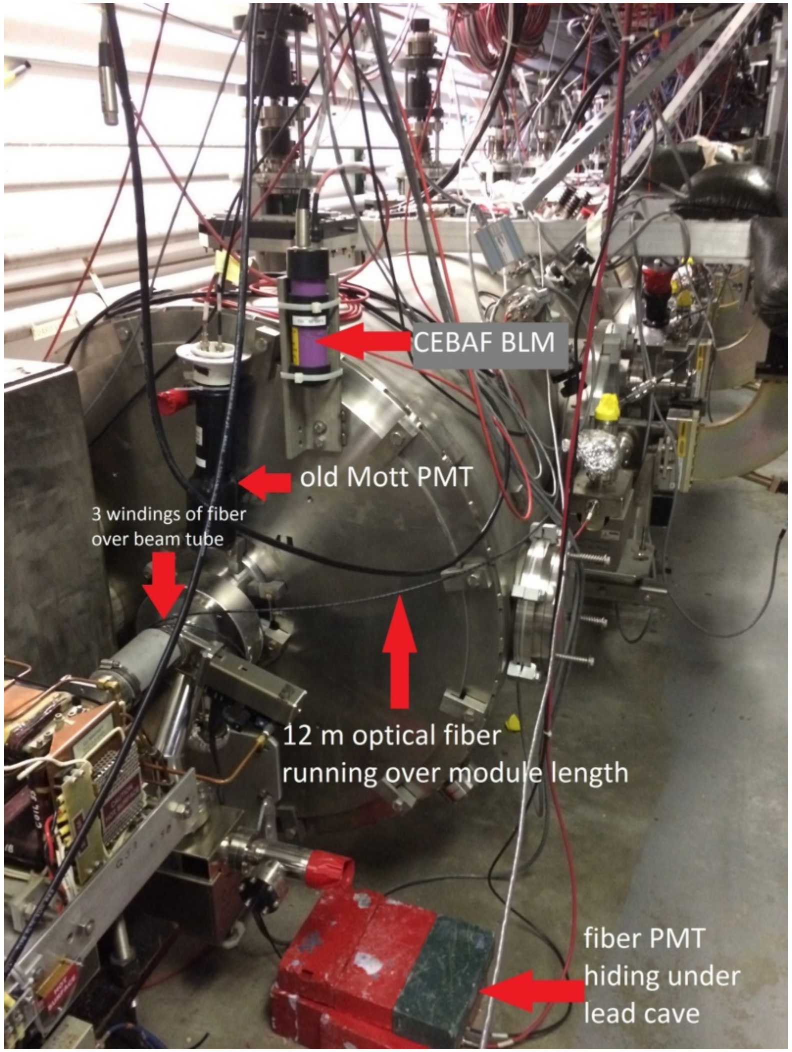
- Two ICs (US 1L25 & 26) both reacted to gradient changes in 1L11, 12 & 13
- Gradient scanning in1L22 had no impact
- Other cryomodules in north linac at nominal gradients
- Long distance (>100 m) transportation of captured FE electrons over 15 modules
- Effect observable by CEBAF BLMs (more later)

General Guidelines for FE Mitigation

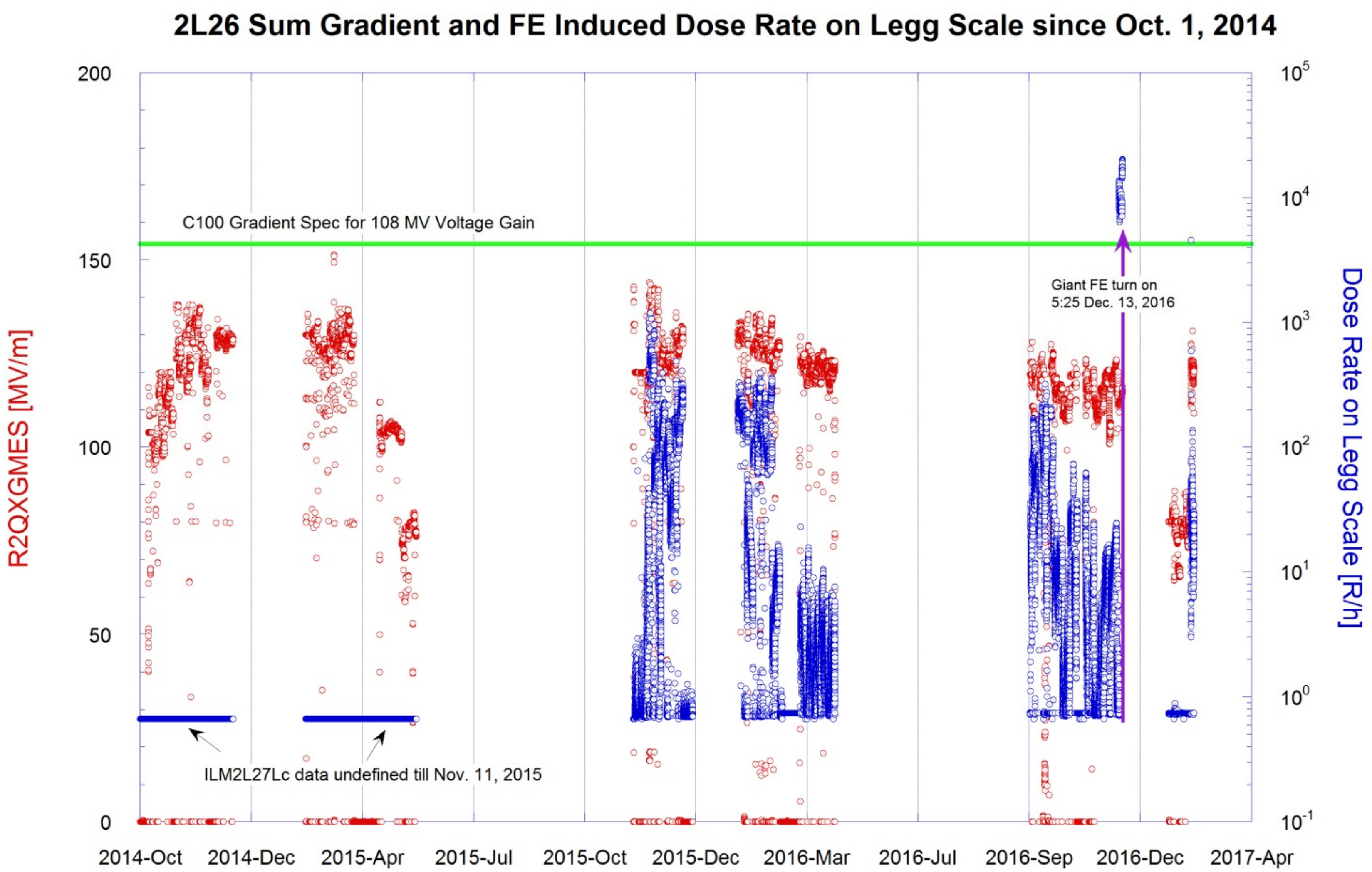
- Get to know which cavity is a FE source cavity and Turn its gradient down – online detector required
- Re-distribute gradient for reduced radiation while preserving integrated accelerating voltage
- Place FE-free cryomodules upstream of a linac and heavy FE cryomodules downstream
- Choose a set of inter-cavity spacing and inter-cryomodule spacing such that the backward propagation of field emitted electrons can be reduced (the forward propagation cannot be mitigated by this technique due to requirement for the main electron beam)

BLMs as Permanent FE Detectors

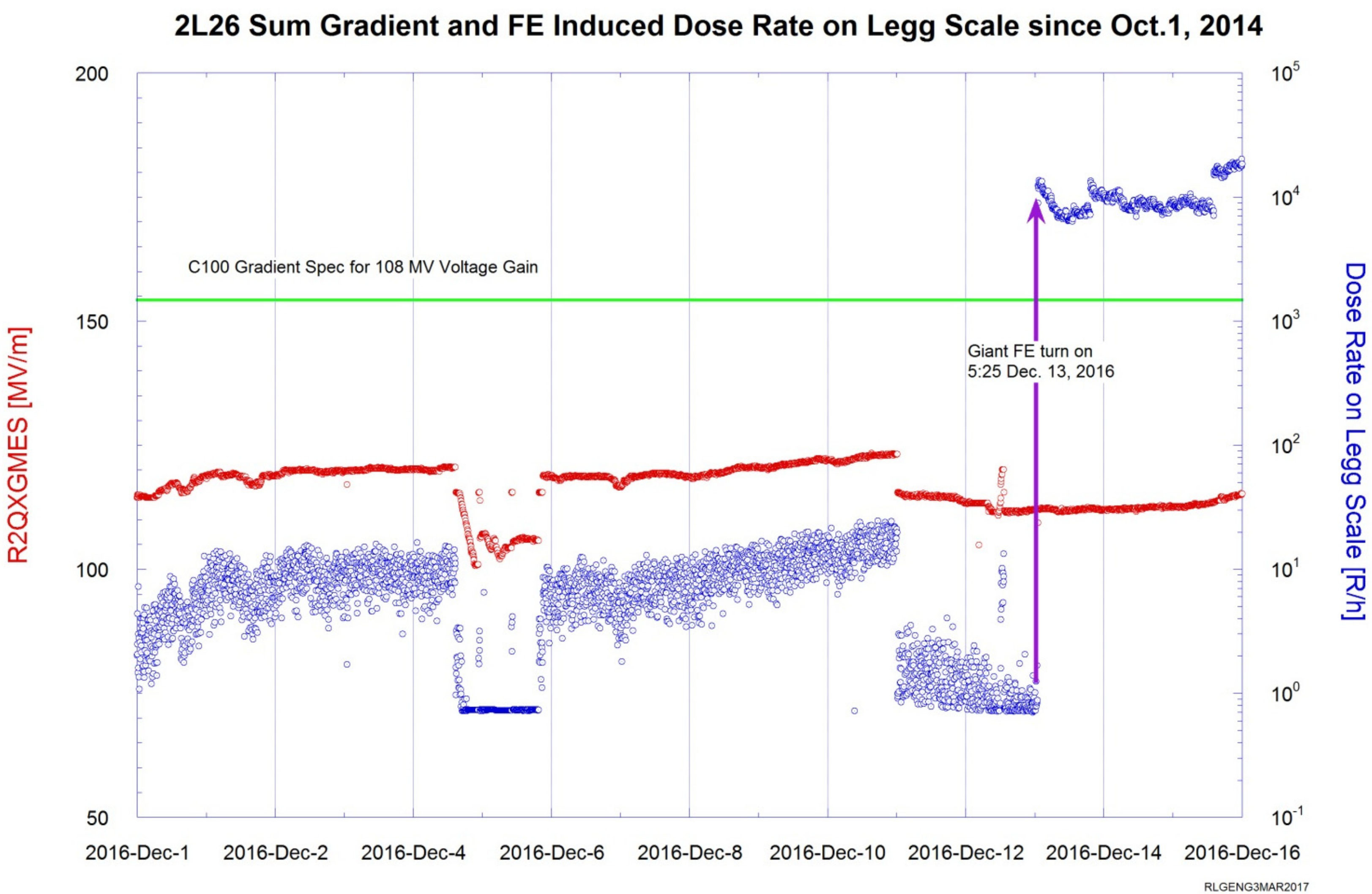
- "Discovery" of BLM sensitivity to FE
  - Systematic check of BLM sensitivity to FE in all C100 zones except 1L22 & 2L25
- CEBAF BLM: PMT (Burle 931B) built into hosing of ABS plastics
- Scintillation and Cherenkov radiation in glass envelope of tube
- Nearly each cryomodule in CEBAF has a BLM attached to its upstream endplate
  - Photo at right is example at 0L04, also shown other added detectors (PMT, fiber)
- Crude calibration was made by using ion chambers at 1L25 & 26



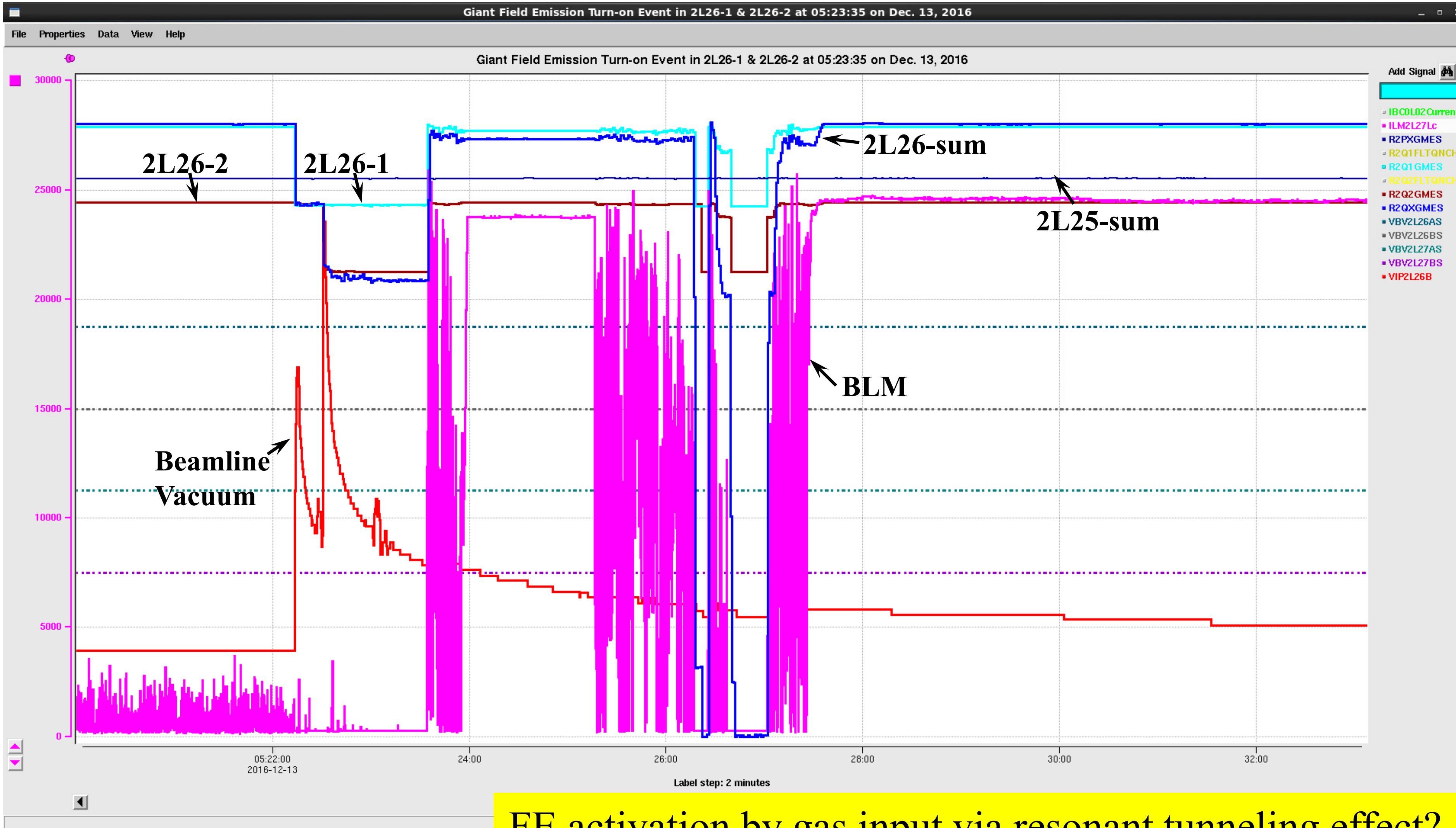
Long Term FE Trend as Observed by BLM



Direct Observation of FE Turn On Event

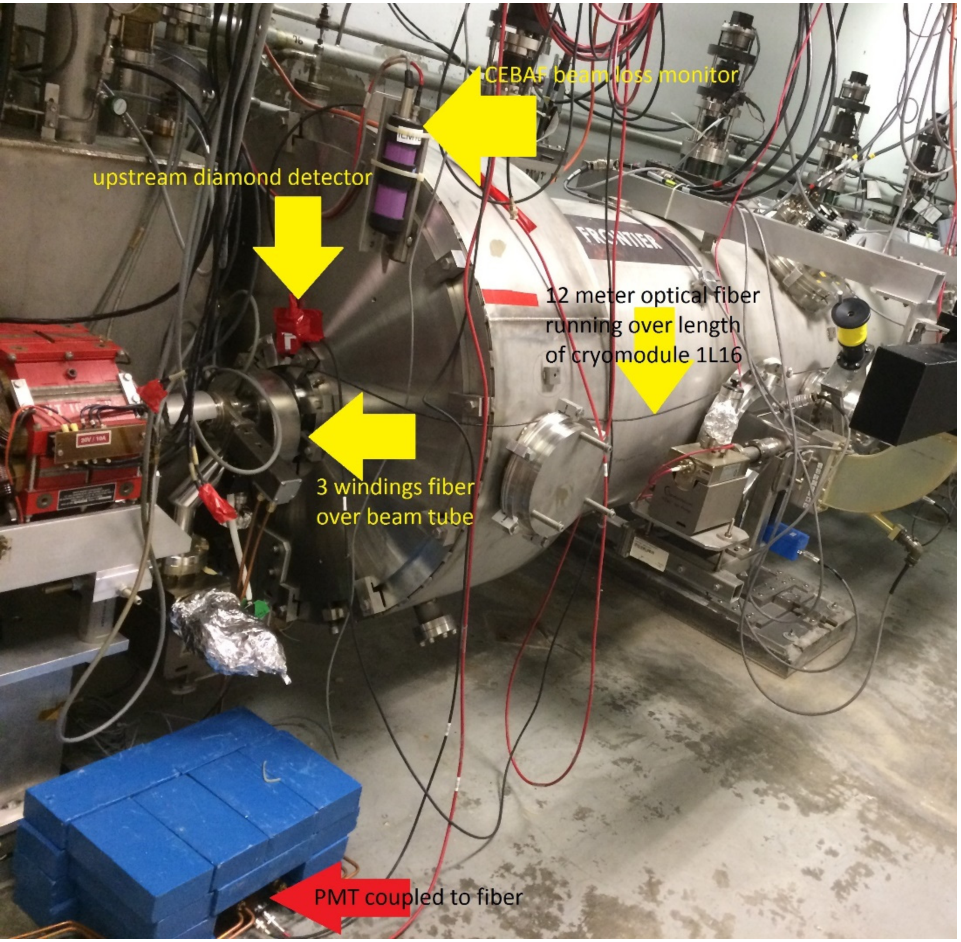


Correlating FE Turn-on w/ Beamline Vacuum Bursts



FE activation by gas input via resonant tunneling effect?

Testing New Detectors for FE Instrumentation



- High-rad optical fiber and diamond detectors tested at CEBAF
- One each diamond detector placed US & DS at 1L26 in North Linac
- 12-m long optical fiber was laid across the 8-m long cryomodule.
- Compared to BLMs and diamonds, the fiber was significantly more sensitive to signals from the interior cavities in 1L26, and less sensitive to crosstalk from cryomodule 1L25

See next talk by A. Fisher

Conclusion

- Introduced FE and discussed unique aspects of FE in large-scale high gradient CW SRF linacs using CEBAF's two 1.1 GeV linacs as example
- Establishing a need for FE instrumentation to improve energy reach and reliability of such linacs
- Reported some initial results toward an improved understanding of FE in CEBAF SRF linacs
- Presented some general guidelines for FE mitigation
- Future developments are needed in testing radiation hard detectors – optical fiber appears promising
- Future SRF projects should consider equipping cryomodules with FE sensors from the design phase of cryomodules

Acknowledgment

- Sasha Zhukov of ORNL for loaning a SNS beam loss monitor
- Tommy Michaelides for assistance in CEBAF beam loss monitors
- CEBAF machine operators for assistance in scanning cavity gradients

Thank you for your attention