Field Emission Studies in CEBAF and Update on HEHG SRF Cavities at JLAB

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Background

- JLAB high gradient SRF R&D re-started in August 2017 due to DOE funded Advanced Accelerator Technology project under US-Japan Cooperation in HEP
  - Collaboration with FNAL, Cornell and KEK, Kyoto U. and Peking U.
  - This allowed us to move forward toward first 9-cell LSF cavity
  - This allowed us to come here and meet LCC community
- CEBAF 12 GeV era beam operation began since January 2014 including 80 new low-loss shape cavities
  - CEBAF at CW high gradient frontier
  - Opportunity for studying high field SRF phenomenology
  - One key issue of interest is understanding and mitigation of field emission from cavity vertical test to long term beam operation in accelerator system

Central Theme

High Efficiency High Gradient (HEHG) SRF cavities

- Topic of fundamental importance in accelerator science and technology

- HEHG SRF has unique applications for ILC in
  - Higher ILC luminosity
  - 1 TeV energy reach
  - Cost saving in construction and operation

- HEHG SRF enables higher gradient for CW machine

http://agenda.linearcollider.org/event/6389/contributions/30619/attachments/25290/38939/Update_high_gradient_high_efficiency_cavity_LCWS14_RG_6oct14.pdf

Key Issues

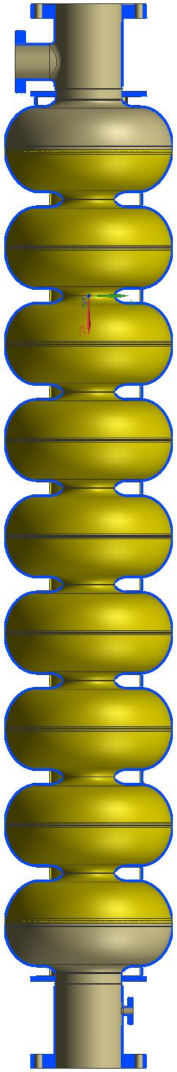
- RF critical field
  - What is ideal superheating field for type II superconductors with κ 1-30 at $T \ll T_c$?
  - What is the nature of "weak spot" where breakdown initiates?
- High efficiency cavity shape
  - What is the best geometrical shape for HEHG cavities?
  - What has been learned from past effort in "cavity shapes alternative to TTF"?
- Field emission
  - Is field emission a bottle neck for Eacc > 40 MV/m?
- Q-slope
  - Origins still unclear, even for Nb
  - Key issue for any "new" material beyond Nb
- Reliability for beam operation in accelerator system

Approaches to HEHG SRF Cavities

- LSF <u>**cavity shape**</u>
  - Fine-grain (FG) Nb
  - Large-grain (LG) Nb
- <u>**Field emission understanding and control**</u> via instrumented test
  - FE mapping at vertical cavity testing
  - Fast X-ray detection at modules in CEBAF
- 1-cell cavity studies of alternative <u>**cavity treatment**</u>
  - Reduce field emission by 1200 C heat treatment
- Cavity treatment with "nitrogen infusion" invented at FNAL (being done by Pashupati Dhakal, see his talk at this workshop)
- Long term interest in coated cavity technology
  - This has been an on-going effort at JLAB

LSF Shape Design

		TESLA	Low-loss/ICHIRO (LL)	Re-entrant (RE)	Low-surface-field (LSF)	CEBAF Upgrade (LL)
frequency	MHz	1300	1300	1300	1300	1497
Aperture	mm	70	60	60	60	53
Epk/Eacc	-	1.98	2.36	2.28	1.98	2.17
Hpk/Eacc	mT/(MV/m)	4.15	3.61	3.54	3.71	3.74
Cell-cell coupling	%	1.90	1.52	1.57	1.27	1.49
G*R/Q	Ω^2	30840	37970	41208	36995	36103



- 20% more efficient as compared to TESLA shape
- 12% gain in Hpk/Eacc, therefore also permitting gradient margin
- Keep Epk/Eacc the same, therefore avoid field emission at high gradient
- Impact from lower cell-cell coupling expected to be manageable

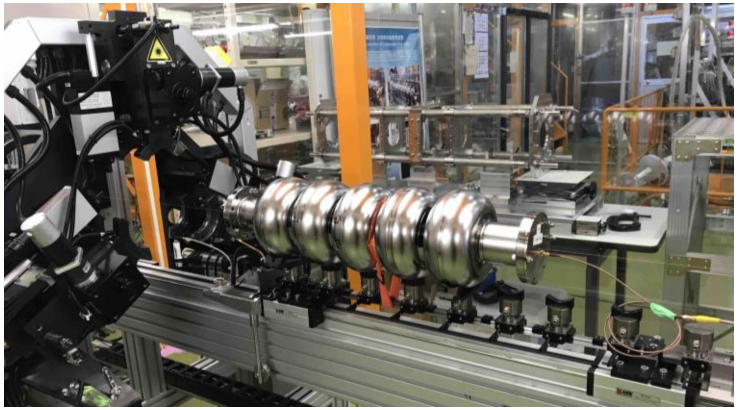
Z. Li, C. Adolphsen, A New SRF Cavity Shape with Minimized Surface Electric and Magnetic Fields for the ILC, LINAC08 (2008).
R.L Geng et al., Development of Ultra High Gradient and High Q0 Superconducting Radio Frequency Cavities, IPAC13 (2013).

LSF Prototype Cavities

- Two 1-cell LG Nb cavities built and tested
  - Both reached Eacc 37-38 MV/m after BCP surface processing
  - LSF1-3 reached > 40 MV/m with additional ILC-style surface processing
    - Presently being evaluated by Pashupati Dkahal with “N infusion” treatment
  - LSF1-2 showed strong FE after ILC-style surface processing
    - Presently being evaluated for FE reduction with 1200C 48 hour heat treatment
- First 5-cell FG Nb cavity completed fab.
  - Presently shipped to KEK for tuning
- Toward first 9-cell fine-grain Nb cavity
  - A new portable CMM is at hand to help address the challenge of small cell-cell coupling

LSF1-2, LSF1-3
Large-Grain
IPAC2015,
WEPWI013

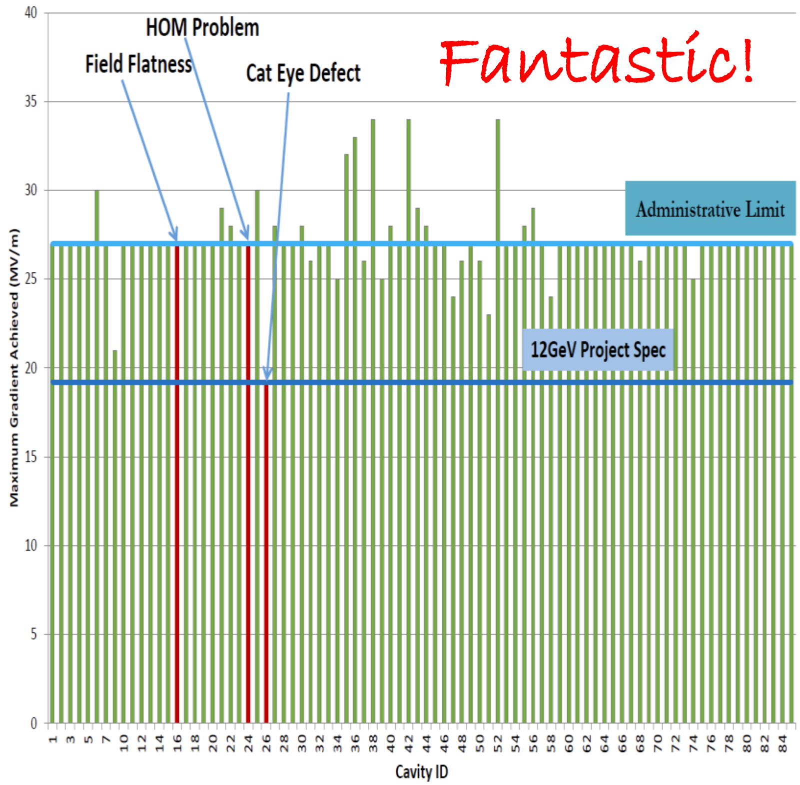
Complete set of half cells for first 9-cell LSF9-1 in hand

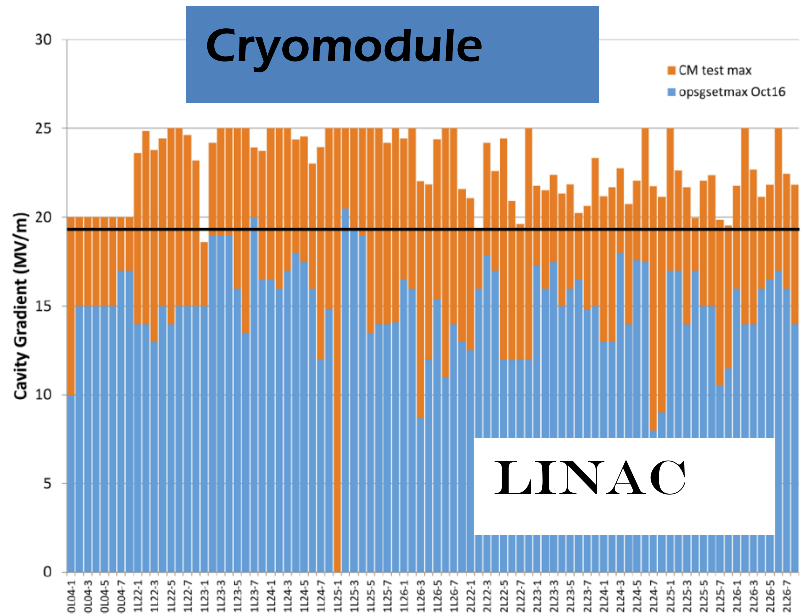


5-cell LSF5-1 fine-grain Nb tuning for field flatness at KEK
Photo curtesy Hitoshi Hayano

"Gradient Degradation" in CEBAF

Final qualification ***individual cavity***



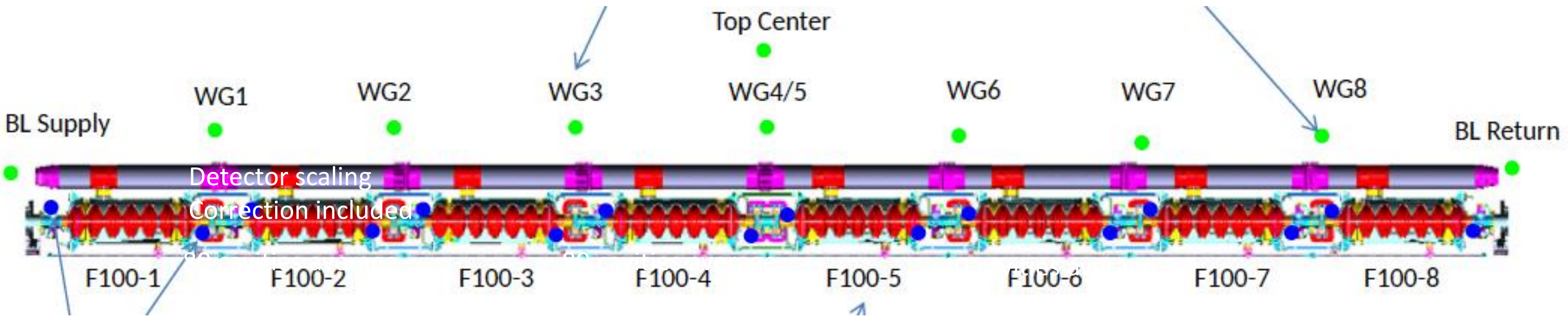


- Why can't cavities run in linacs at gradients as in cryomodules?
- Root causes being studied: FE a principal issue of interest

Degradation of FE Onset

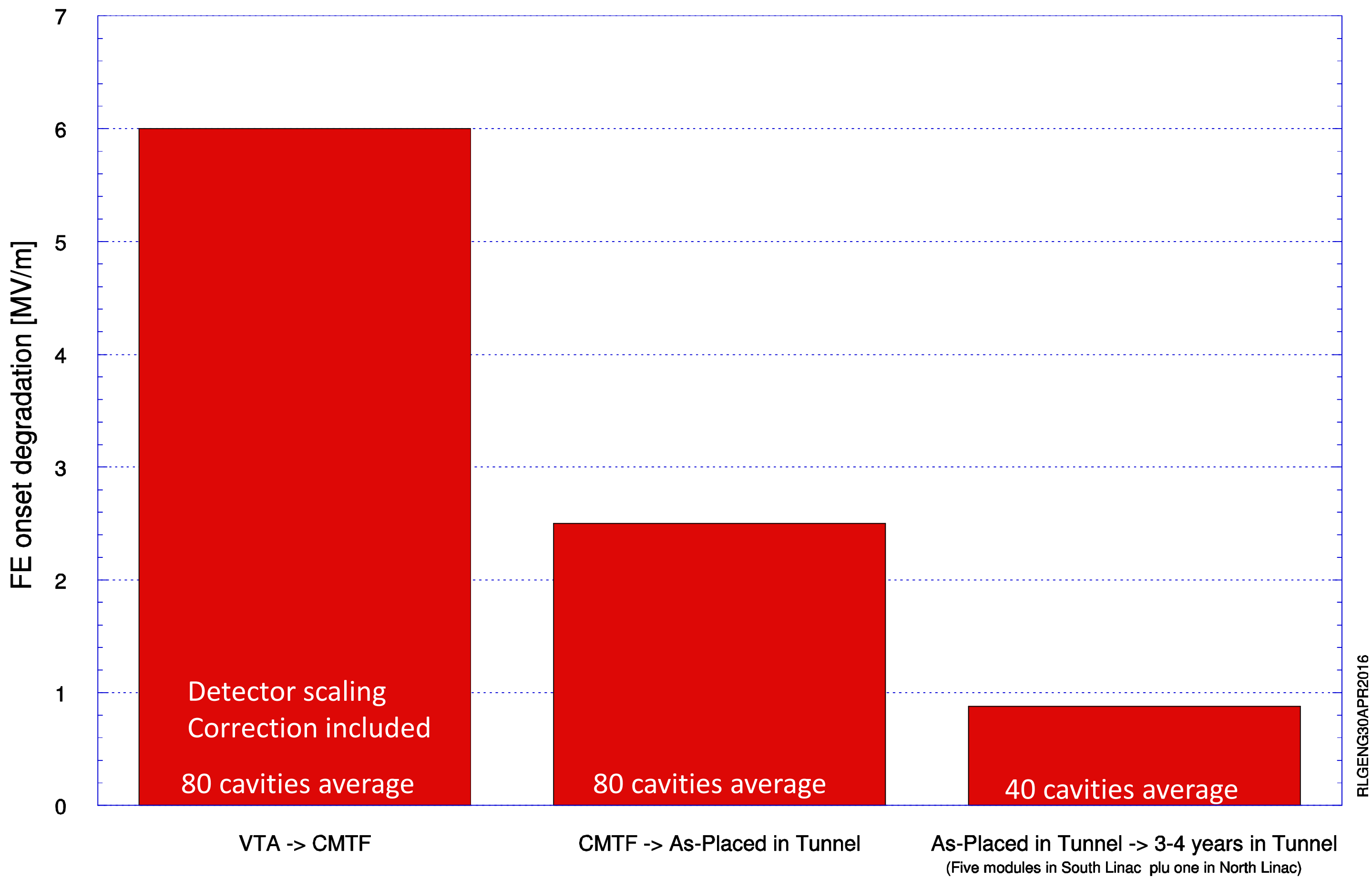
- Universal definition of FE onset still lacking
- "At cavity X-ray detection" for improvement

- 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



WEPWI012, IPAC15

Degradation of FE Onset



IPAC16
THOBB03

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)

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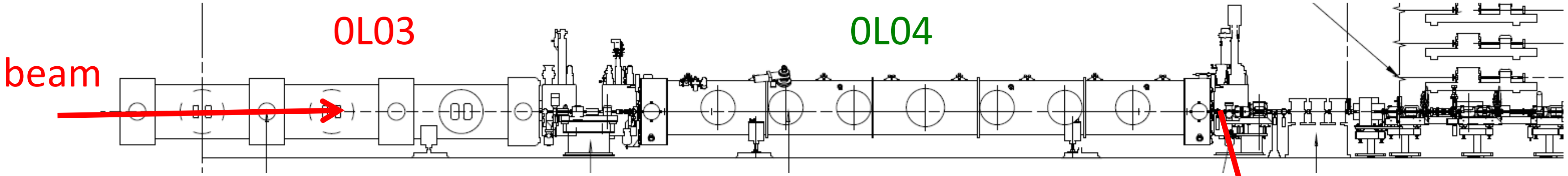
Conservation of FE Onset

- Control particulate input during string assembly
  - Improved clean room procedure applied to the latest refurbishment module C50-13
  - On-going LCLS-II work demonstrated marked improvement with modules (p-CM, CM1, CM2) tested at JLAB
- Reduce particulate input during accelerator operation
  - CEBAF ion pump and gate valve operation procedure improved
- Reduce gas molecules input over long term accelerator operation
  - NEG pump replaced ion pump in C50-12 and C50-13 for beamline vacuum
- Understand and mitigate particulate transported by CEBAF main electron beam
  - Analysis of particulates collected from cavities operated with beam for long term
    - Direct evidence of transported Ti/Ta bearing particulates (SRF2015, MOPB035)
    - On-going effort with CEBA module refurbishment C50-12, C50-13 (SRF2017, TUPB106)
  - Work is on-going in modeling the process of particulate charging, levitation and beam-enabled transportation (He Zhang of CASA)

FE Challenge in SRF Accelerators

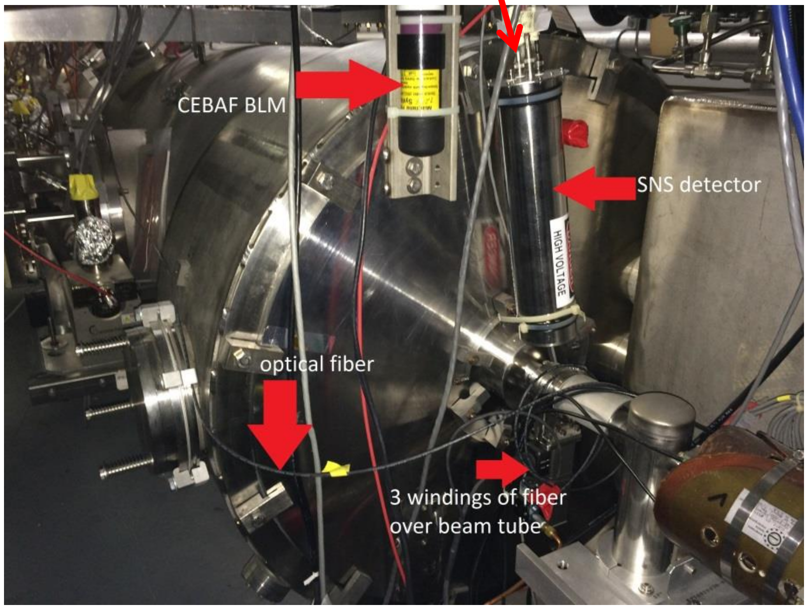
- Impact: energy reach, reliability and maintainability
- Unique aspects
  - FE electrons charging ceramic windows in RF couplers causing fast trips as was understood for original CEBAF cryomodules
  - FE electrons captured, transmitted into other cryomodules and gain increasingly larger energies, causing 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 – 100 MeV Zones

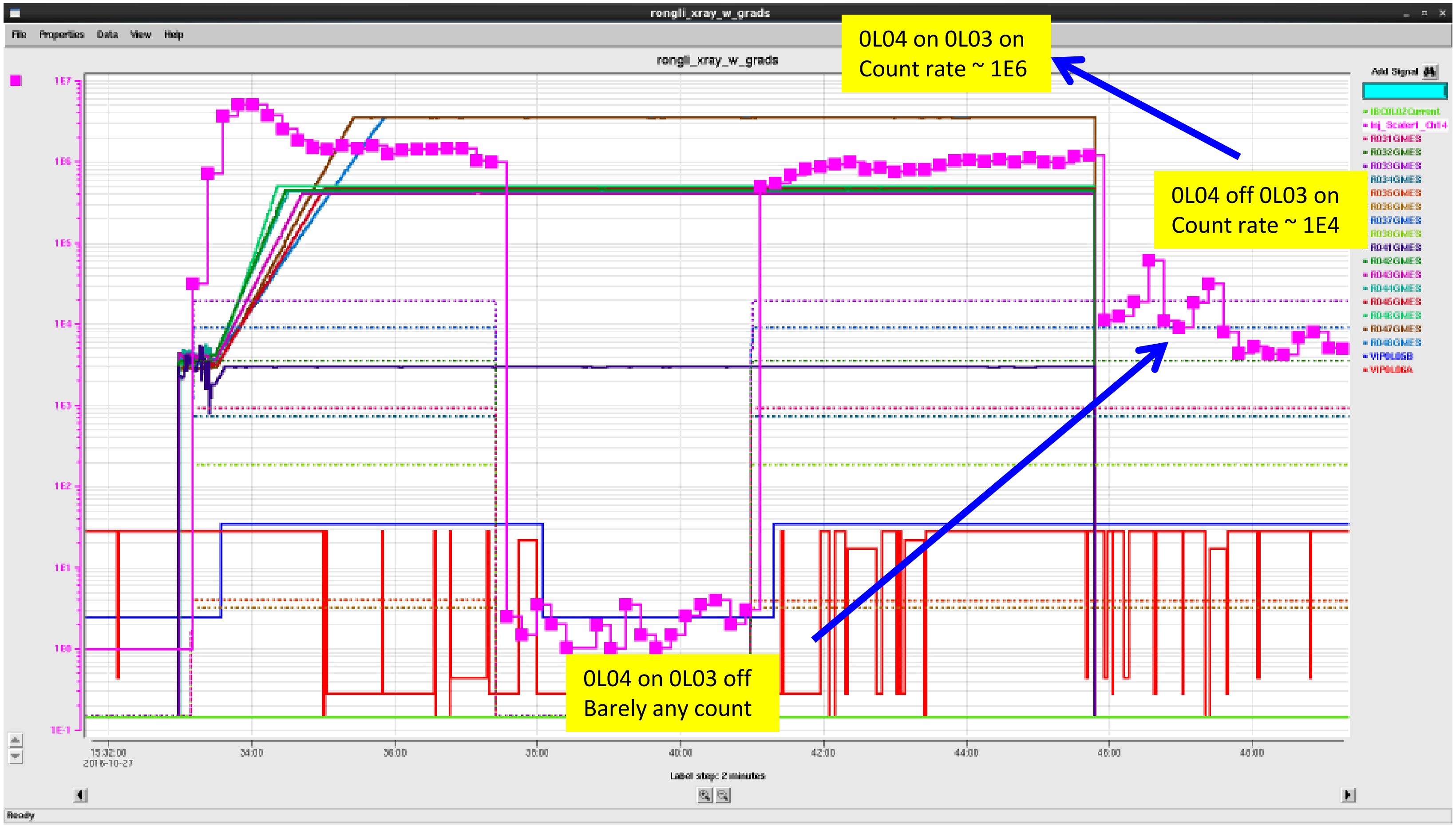


- Tests done in the injector zones 0L03 (C20) and 0L04 (C100)

- SNS-type fast beam loss monitor (plastic scintillator + PMT) attached to the downstream endplate of cryomodule in zone 0L04.

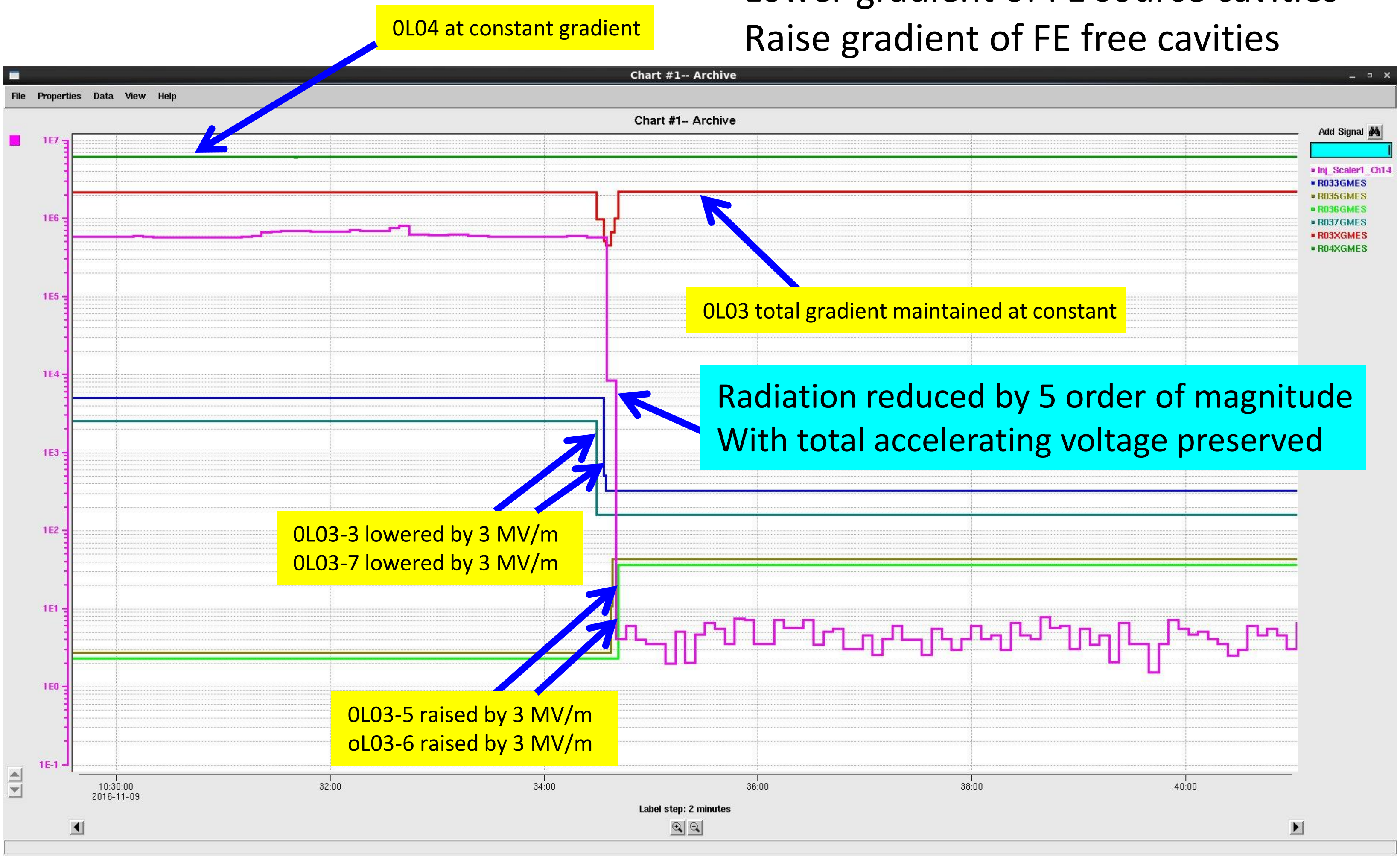


Radiation Enhancement Effect Observed



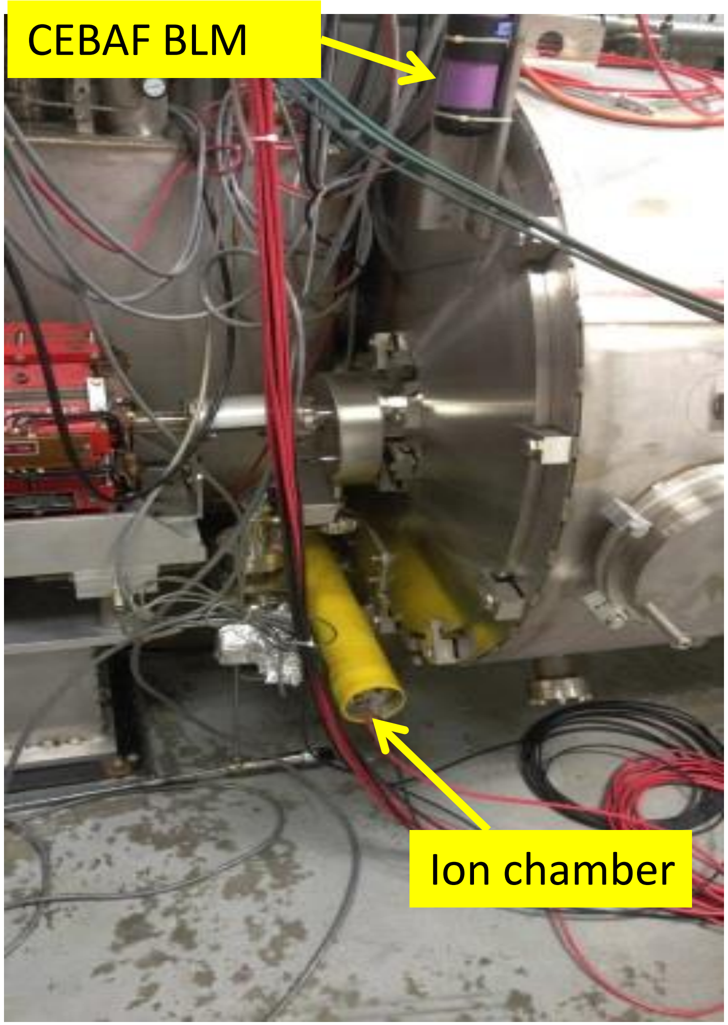
Radiation Reduction by Gradient Redistribution

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

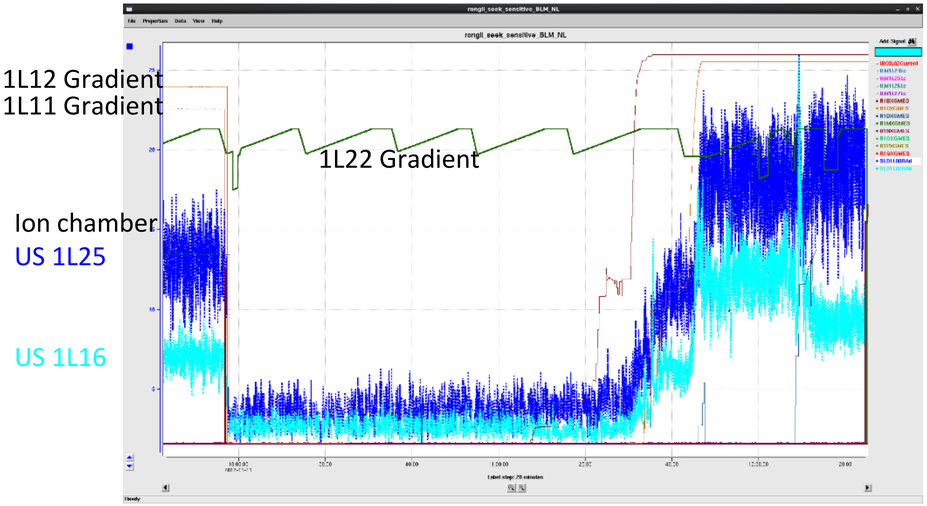


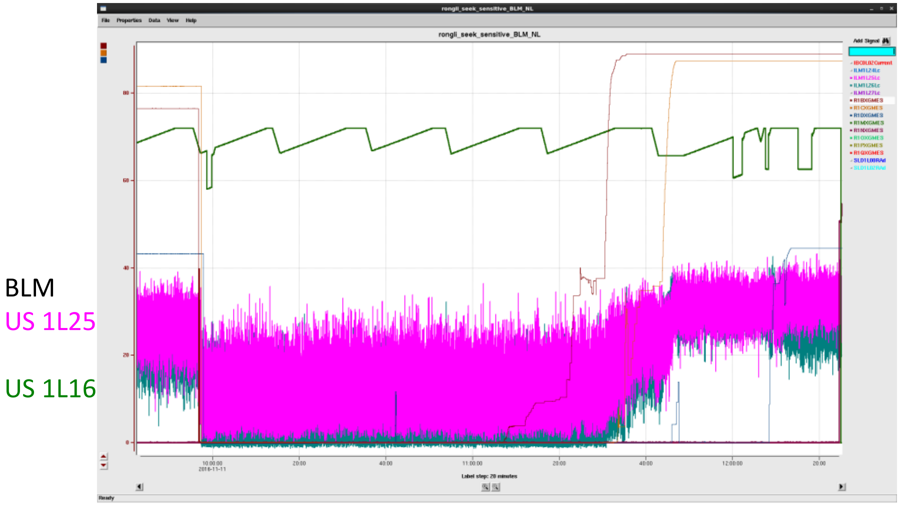
Propagation of FE Electrons – 1GeV Zones

- 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 in 1L22 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

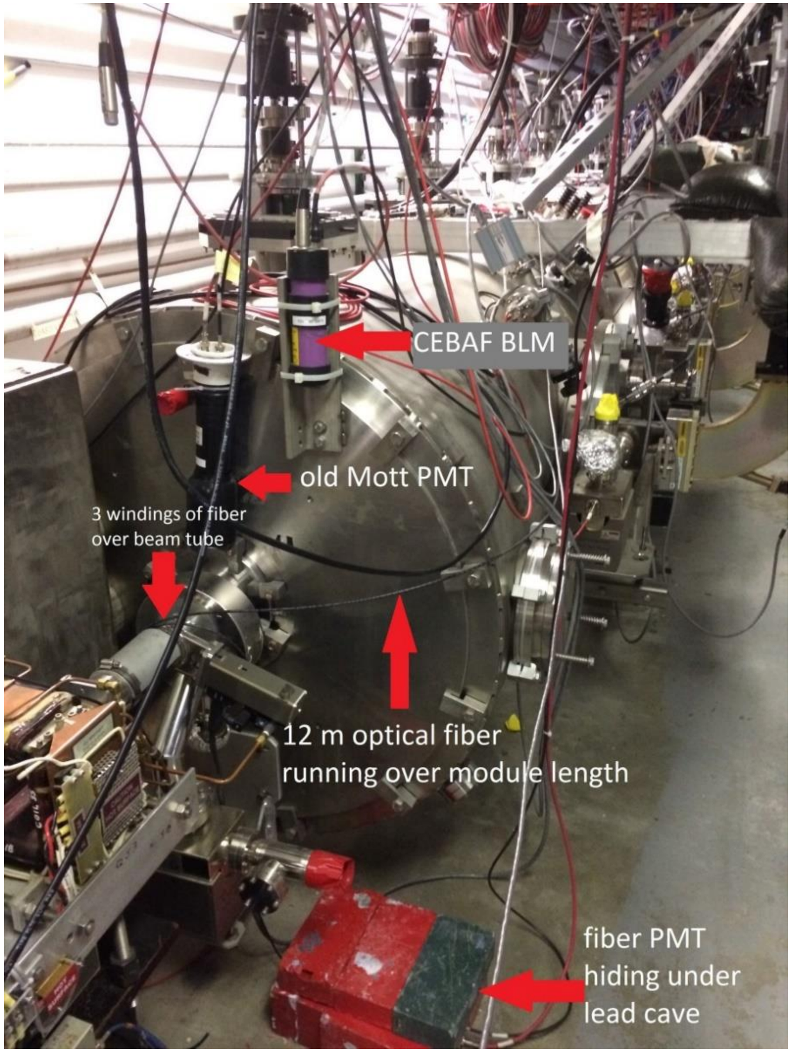
- Re-distribute gradient for reduced radiation while preserving integrated accelerating voltage

- Place FE-free cryomodules upstream of a linac and heavy FE cryomodules downstream

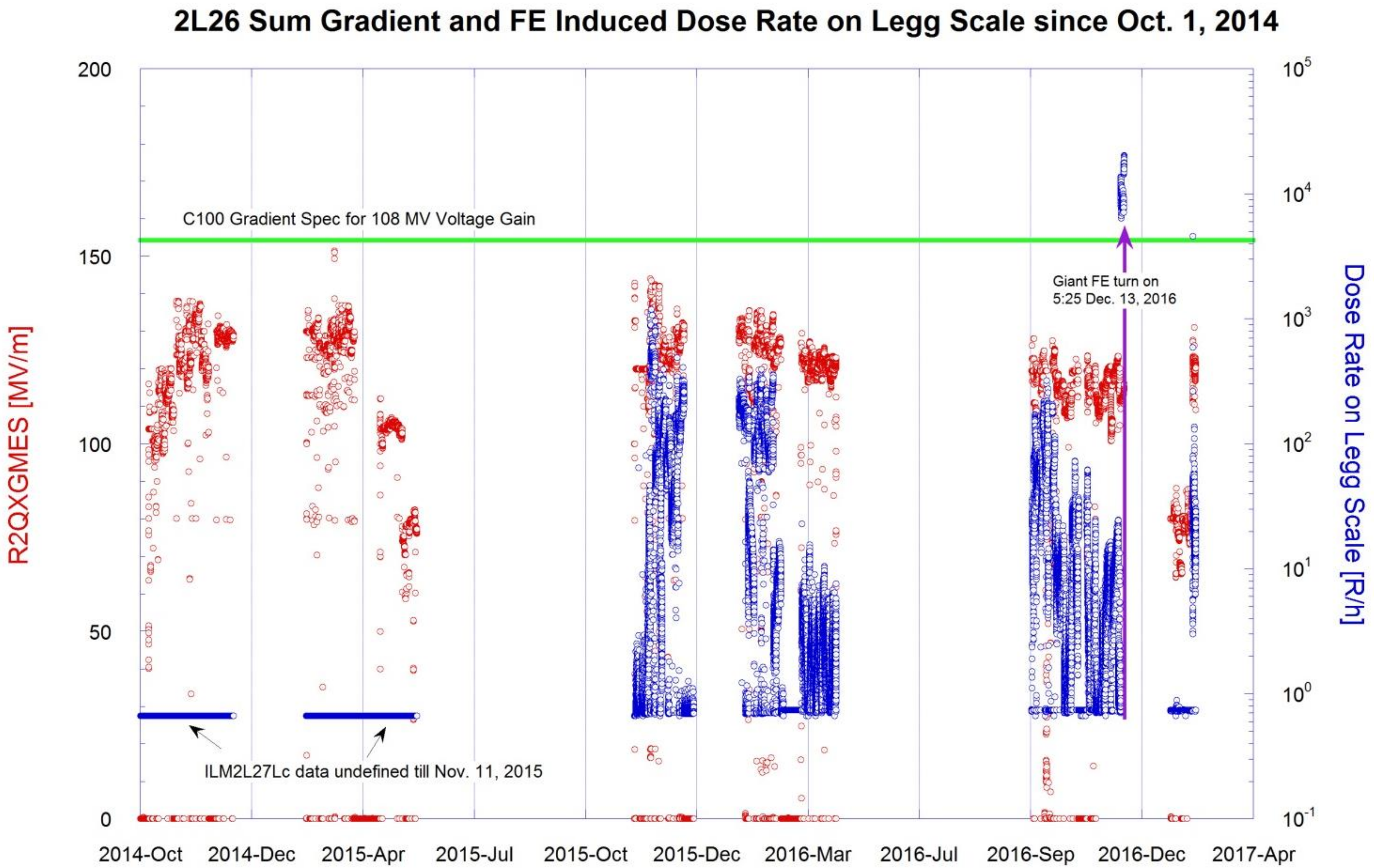
- Choose a set of inter-cavity spacing and inter-cryomodule spacing such that the backward propagation of field emitted electrons can be reduced (the forward propagation cannot be mitigated by this technique due to requirement for the main electron beam)

BLMs as Permanent FE Detectors

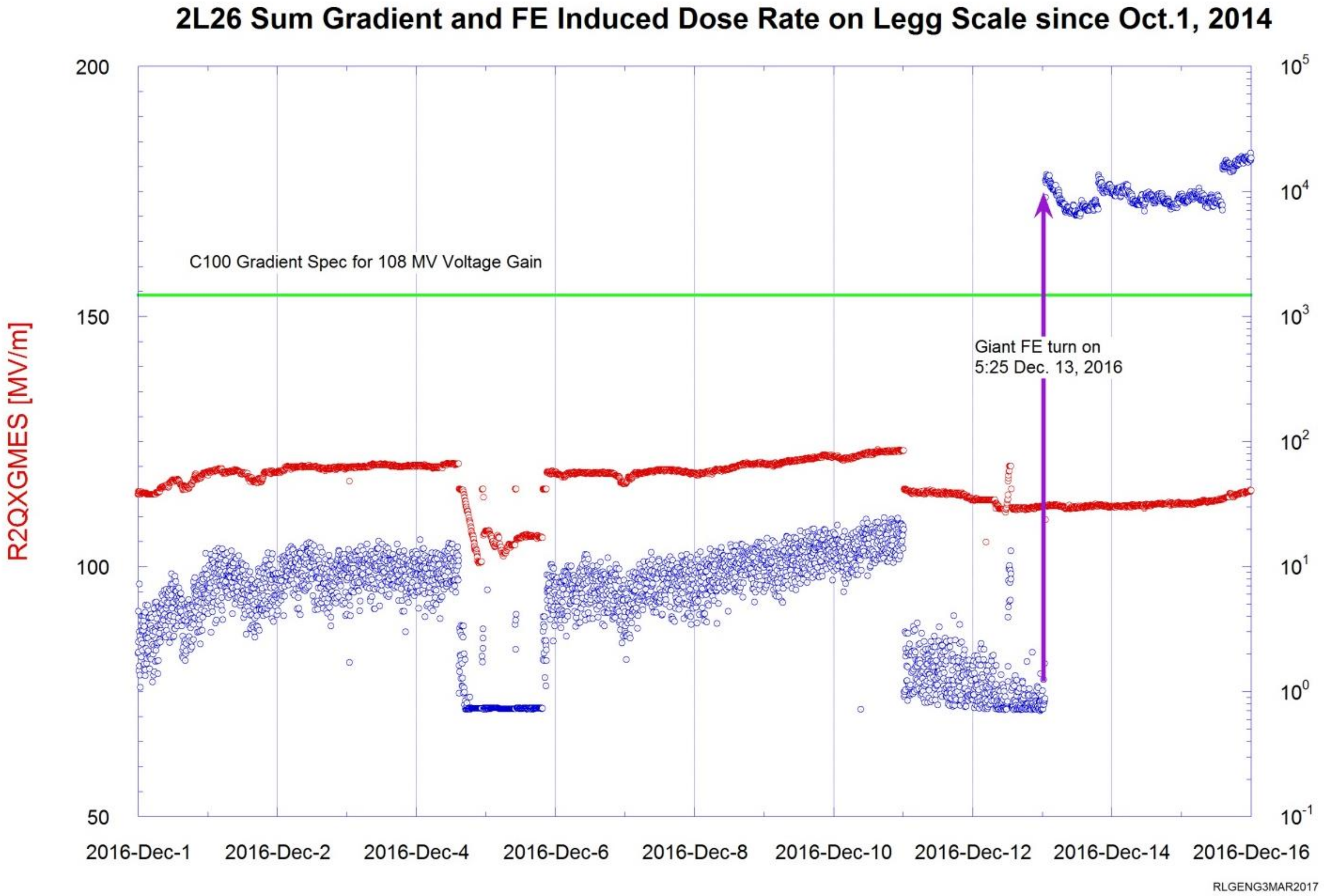
- Observation of BLM sensitivity to FE
  - Systematic check of BLM sensitivity to FE in all C100 zones except 1L22 & 2L25
- CEBAF BLM: PMT (BURLE 931B) built into hosing of ABS plastics
- Scintillation and Cherenkov radiation in glass envelope of tube
- Nearly each cryomodule in CEBAF has a BLM attached 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



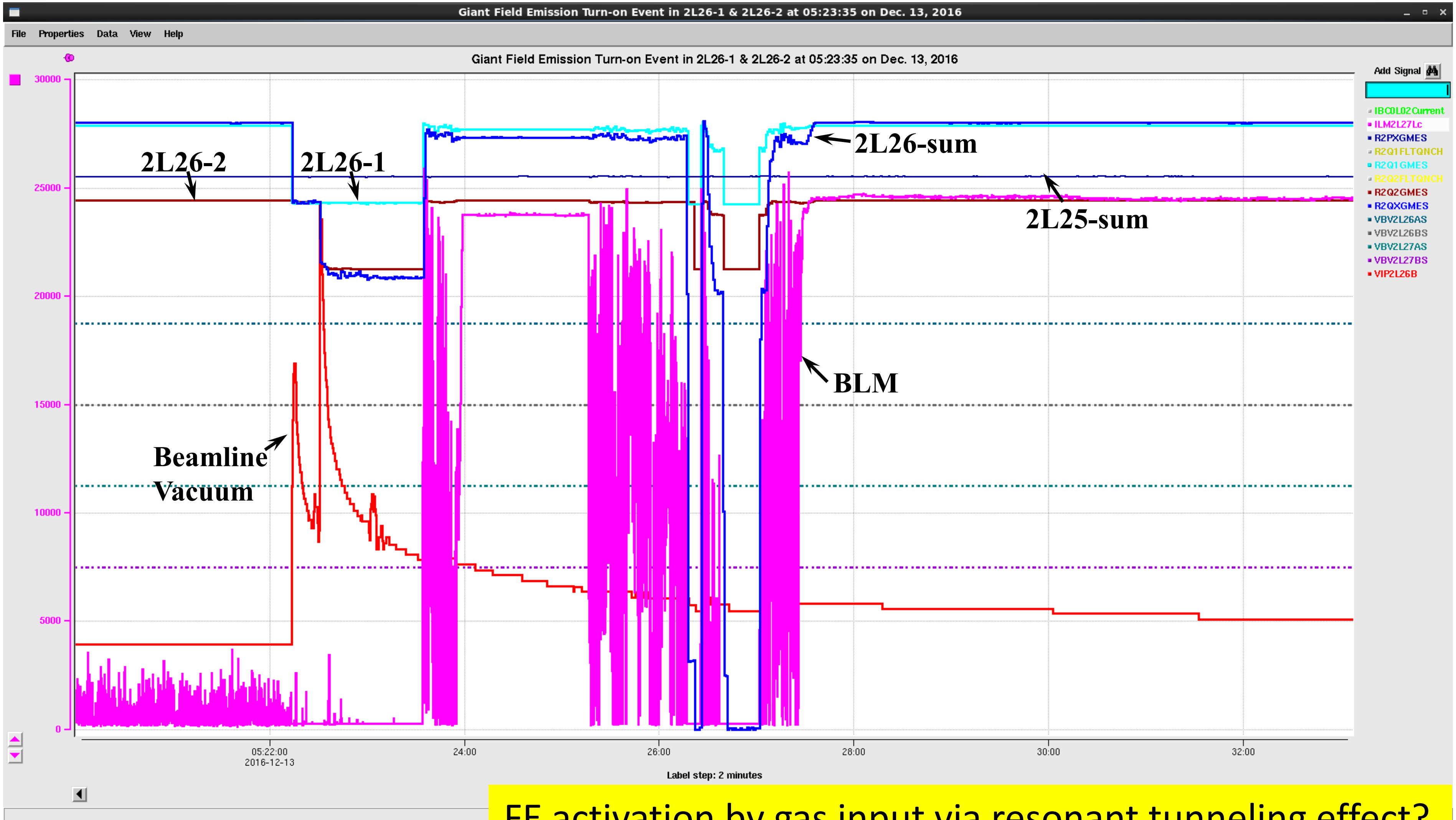
Long Term FE Trend as Observed by BLM



Direct Observation of FE Turn On Event

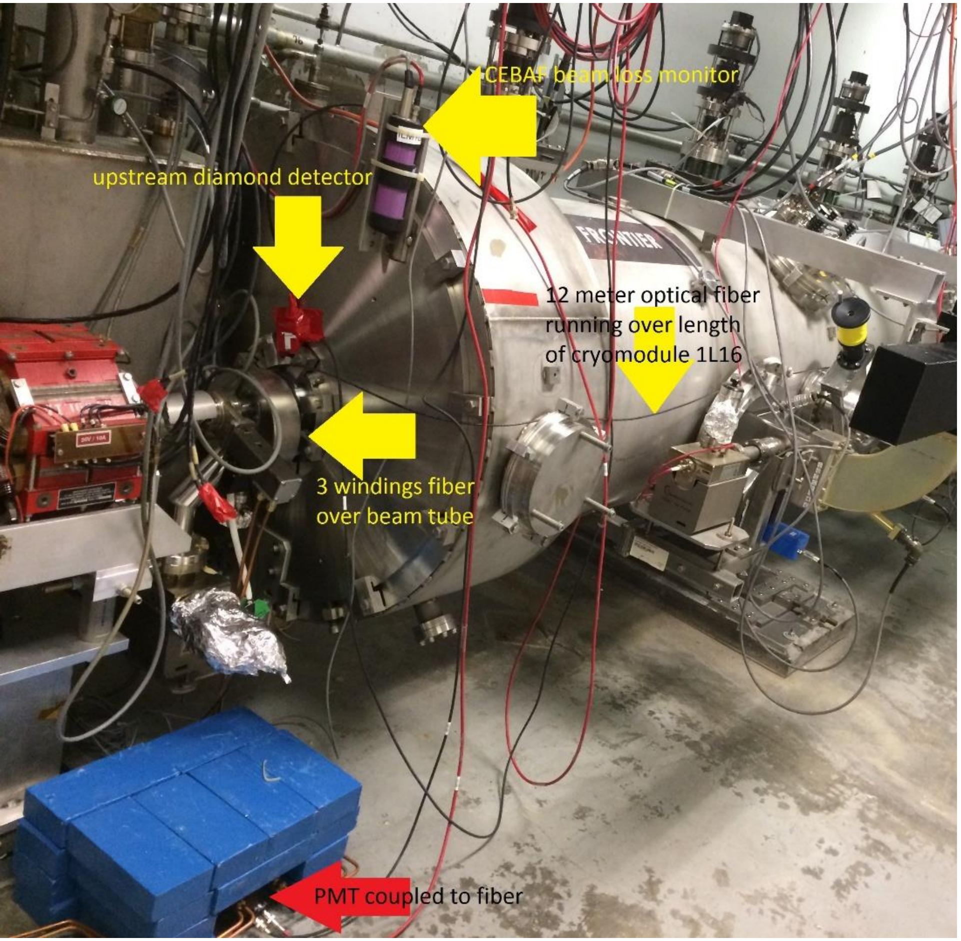


Correlating FE Turn-on w/ Beamline Vacuum Bursts



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 in Jan. 2017
- 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 in1L26, and less sensitive to crosstalk from cryomodule 1L25

Collaboration with Alan Fisher of SLAC

Conclusion

- Our interest in developing HEHG SRF cavities remains high due to its fundamental value and useful applications in ILC for higher luminosity, 1 TeV upgrade, and cost saving.
- JLab adopted LSF shape + Large-grain Nb material as technical approach toward realization of HEHG SRF cavities.
- First 5-cell LSF cavity is being tuned at KEK. Next: proc. and testing
- Work re-started toward first 9-cell LSF cavity.
- We maintained a stable effort in understanding and reduction of FE in full-scale multi-cell cavities as well as cavities placed in accelerator tunnels via X-Ray detection/mapping.
- We got some initial results toward an improved understanding of FE in CEBAF SRF linacs, leading to some general guidelines for FE mitigation.
- We are glad to be back to gathering of LCC community enabled by US-Japan collaboration.

Acknowledgment

- Hitoshi Hayano of KEK for turning 5-cell LSF cavity
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- Jiankui Hao and Kexin Liu of Peking University for collaboration on HEHG SRF cavities
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