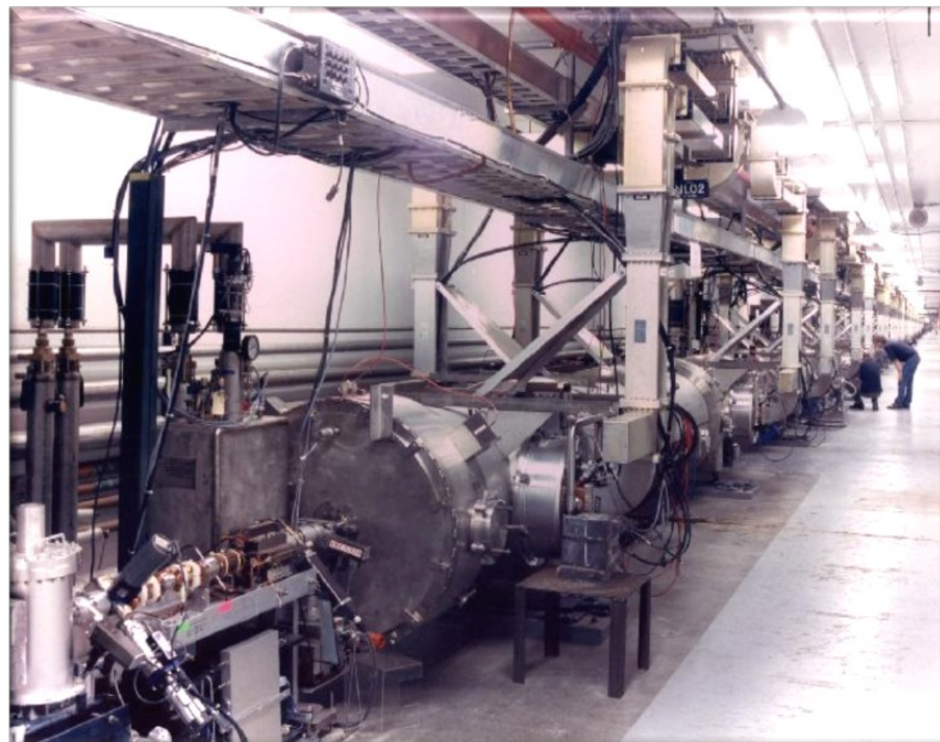
CEBAF Gradient Management

Optimizing cavity performance through collaborative effort



Clyde Mounts

Agenda

- Short CEBAF cryomodule design performance overview
- Operational gradients
- Challenges in maintaining operational gradient
- Gradient Improvement Team
- Progress in optimizing operational gradient
- Summary

CEBAF overview

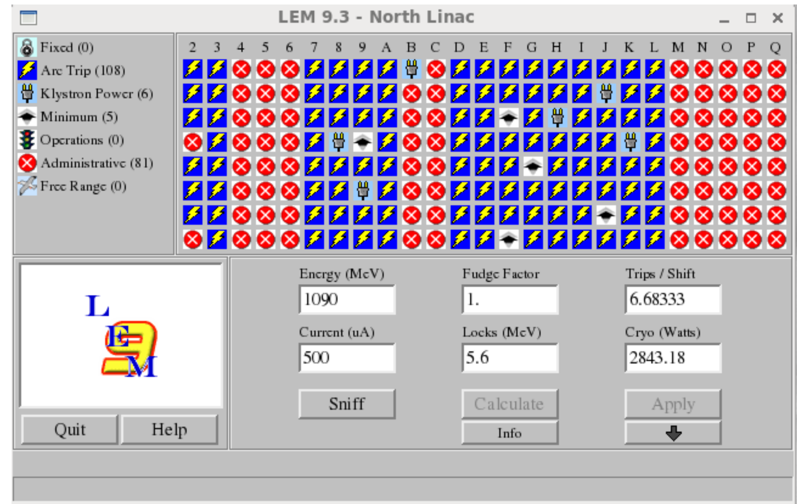
- CEBAF is a recirculating electron particle accelerator with potential to deliver 12 GeV beam to a single experimental hall while delivering up to 11.5 GeV to the remaining 3 halls in CW mode – simultaneously
- There are 418 SRF accelerating cavities in total
  - 18 in the injector region
  - 400 in the north and south linacs
- There are 3 distinct “flavors” of cryomodules
  - C20: 5 cell cavity structure designed to produce 20 MeV
  - C50: 5 cell cavity structure refurbished to produce 50 MeV
  - C100: 7 cell cavity structure designed to produce 108 MeV
- C20 and C50 cryomodules share a similar control system
  - Computer controlled/analog based – designed in the 1980s
- C100 zones have new DSP I/Q control system
  - Handles the higher Qext and Lorentz detuning

Operational gradient

- Operational gradient is the voltage a cavity will operate at stably.
  - Statistically and empirically derived values
  - Based on and not to exceed commissioning gradient values
  - The gradient delivery system performance is dynamic, so the operational value may change over time
  - During run-time, the Operations crew or RF support group will de-rate cavities due to performance issues
  - For C50/100 modules, operational gradient should always be equal to beam calibrated commissioning gradient; if not -
    - Identify and fix the problem - or
    - Revisit beam calibrated commissioning gradient value

Gradient = Gold

The goal is to realize full potential of available gradient and to maintain cavity accelerating voltages over the course of an experimental run. In the 12 GeV era it is critical that each cavity be evaluated so that appropriate actions can be taken to mitigate impact on the experimental programs if optimal gradient is not maintained.



Linac	Type	$\langle E_{maxOPS} \rangle$ (MV)	2014-Feb <GMES> (MV)	2014-Feb $\frac{\langle GMES \rangle}{E_{maxOPS}}$ (MV) (%)	2014-Apr <GMES>	2014-Apr $\frac{\langle GMES \rangle}{E_{maxOPS}}$
NL	C20	8.61	7.19	84	5.26	61
NL	C50	11.71	11.03	94	10.11	86
NL	C100	20.86	17.59	84	17.78	85
SL	C20	9.09	7.05	78	6.70	74
SL	C50	11.55	10.06	87	9.16	79
SL	C100	19.77	16.66	84	15.90	80

Table 8: $\langle E_{maxOPS} \rangle$ commissioning values from Table 2, <GMES> values from the two sample Spring 2014 configurations (Tables 3 and 7) and their ratio.

A. Freyberger

For our machine, when available gradient goes down, the trip rate goes up

Example: C100 operational gradient degradation

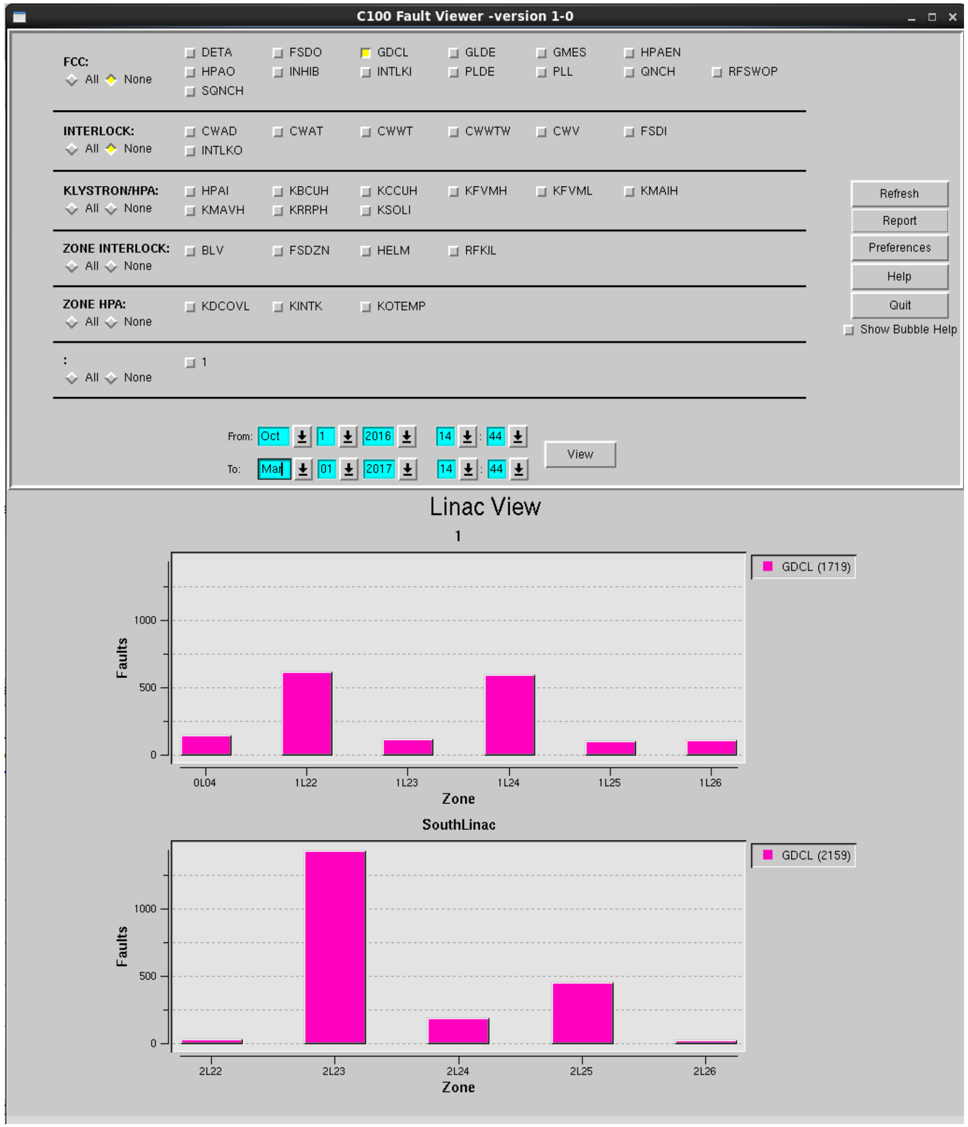
Average for the Final maximum operating gradient – **20.4 MV/m**
Dynamic heat load ≤ **35 W** per cavity / **240 W** for the string.
Static Heat Load ~**18 W**
Average Energy Gain = **113 MV / 108 MV**

Cryomodule	Zone	Commissioned Energy	Operational Energy 2015	Operational Energy 2016
C100-1	SL24	104 MV	77.1	77.21
C100-2	SL25	122	89.6	89.67
C100-3	NL22	108	91.2	91.35
C100-4	SL22	93	91.5	91.56
C100-5	SL23	121	91.9	91.9
C100-6	NL23	111	99.4	91.9
C100-7	NL24	103	95.9	91.84
C100-8	SL26	110	90.7	86.9
C100-9	NL25	105	85.0	83.65
C100-10	NL26	106	83.5	77.28

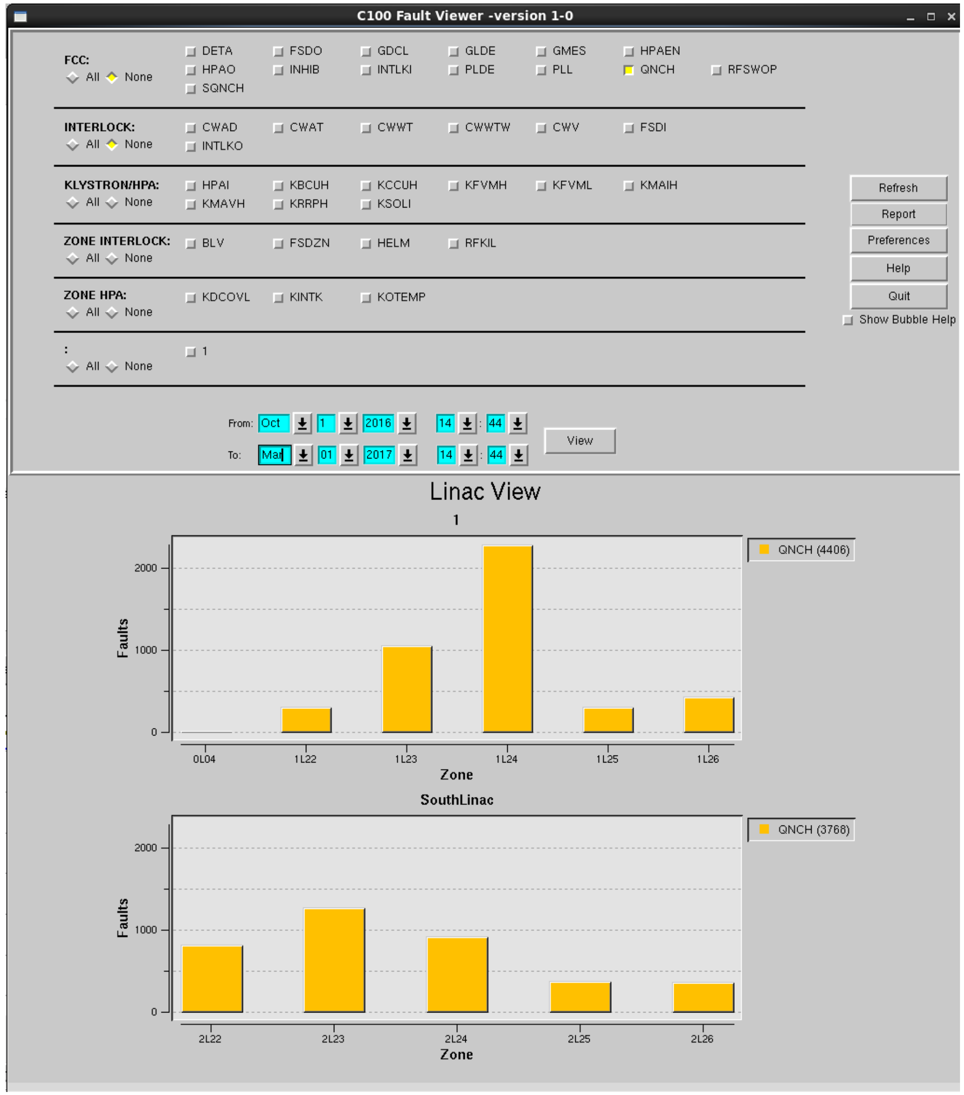
Factors that limit operational gradient

- C20
  - Arc trips
  - Spurious field emitter turn on (wrecks the cavity model)
  - Cryomodule warm up/cool down
- C20/50 cavity klystrons are nearing end of life
  - To prevent tube damage through mod anode leakage heating, the cathode current is reduced via application of mod anode voltage, which lowers available power to the cavity, thus gradient
- C100
  - Microphonics
  - “Fratricide” quench events
  - Cryogenic pressure/ Dynamic heat load
    - C100 smaller helium vessel
    - Critical heat flux in risers for C100 cavities
  - FE effects
    - Cryomodule vacuum seals
    - Warm girder elements and cabling
    - Beamline outgassing from heating
    - Turbo pump death (insulating vacuum)
- All cryomodules
  - Dynamic operational adjustments
  - Hardware failure
  - Component obsolescence
  - “Lost gradient”

GDCL “soft faults”



Quench Faults



Lost Gradient?

- Typically recoverable to some degree – record keeping
- C20 cryomodules
  - Arc rate adjustments
    - If a cavity is detected to be arcing at an unacceptable rate, the cavity gradient is lowered by Ops
    - Until the cavity gradient model is updated, the cavities are hard limited by this activity
- All cryomodules
  - Diagnostics processes
  - Program requirements
  - Repair/recovery activities

Critical and dynamic system – overwhelming burden

Due to the nature of the CEBAF performance requirements, and the importance that a robust gradient delivery system holds, it became increasingly evident that gradient optimization and management was beyond the scope of a linear transitional design, production and operations scheme - and the burden of any one person, group or division.

In 2016, the Gradient Improvement Team was formed.

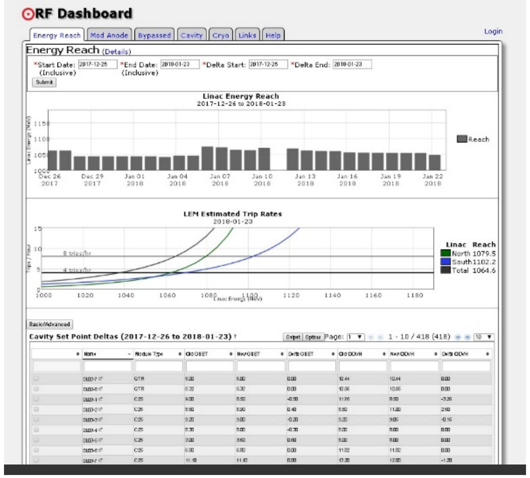
Gradient Improvement Team - Charter

- "The CEBAF superconducting cavities and associated RF systems must provide 1.1 GeV per linac with a total trip rate less than 5 trips/hour while operating within the cooling capacities of the CHL1 and CHL2. At the time the Team is being chartered, these specifications are barely being met, and previous operating experience shows that trip rates increase with time. This creates an urgent need to get the best possible performance out of the installed systems, now and for the future.
- The goal of the Team is to evaluate every aspect of the cryomodule-RF-cryogenics system and optimize the system parameters to maximize the available gradient and minimize the trip rate at the nominal energy of 12 GeV."

In effect, management got a group of "players" together and gave them a hammer to get things done!

Gradient Improvement Team – participating staff

- Collaboration between Cryogenics, Engineering, Operations, Software and SRF divisions
- Tools developed to analyze cavity gradient performance in real time and aid in providing solutions and provide performance forecasts
- Action items assigned to tactically improve gradient reach and strategically ensure robust future accelerator operation
- Improved systems integration process – all divisions share information to pre-emptively avoid problems
- Development of documentation and training



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Analysis and Prioritization

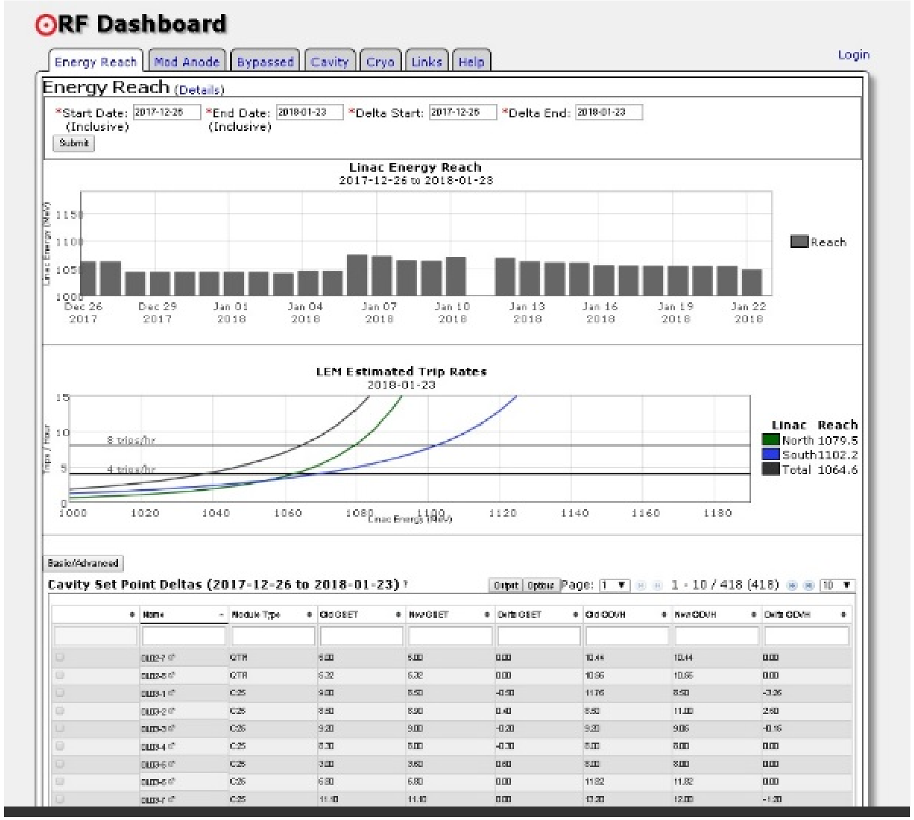
- Each expert on the team contributed to the set of issues that need to be evaluated to optimize the accelerator gradient “system”.
  - Over 70 issues identified
- Devised a way to organize the list into prioritized plans of action.
  - Wanted to understand:
    - Issue grouping
    - What we were gaining by addressing the issue
    - What were the associated costs and benefits
  - Once the solutions for the issues were developed by the SMEs, the cost-benefit rankings could be started
  - Two stages of rankings used for prioritization:
    - Costs and Benefits - Traditional approach using cost, labor, risks, and rewards
    - Weights - Using the Analytic Hierarchy Process (AHP)

Progress examples

- C100 Microphonics dampening improvement
  - Analysis and structural stiffening of waveguide and tuner stalks designed and applied by engineering
- C100 Quench fault reduction
  - Noted unexpected periodicity of trips resulted in statistical analysis and modeling by to isolate contributing cavities – similar to arc rate modeling in C20 zones
- C100 radiation damage reduction
  - SRF and ENG designed and installed lead collars on cryomodule downstream end can to prevent warm girder element and cable damage
- Fault isolation
  - Engineering and software collaborated to develop a fault counter/viewer for historical reference
- Cryogenics adaptations
  - Assisted Operations in finding nominal return pressure for liquid level stability issues
  - Developed option to shed excessive heat from C100 modules

Progress examples – cont'd

- Software developed a web based analysis and display tool
  - Cavity and zone performance characteristics tracked in virtual real time
  - Offers present gradient reach and displays gradient trends to predict scheduling of maintenance days
  - Many other features and readily extensible to include more

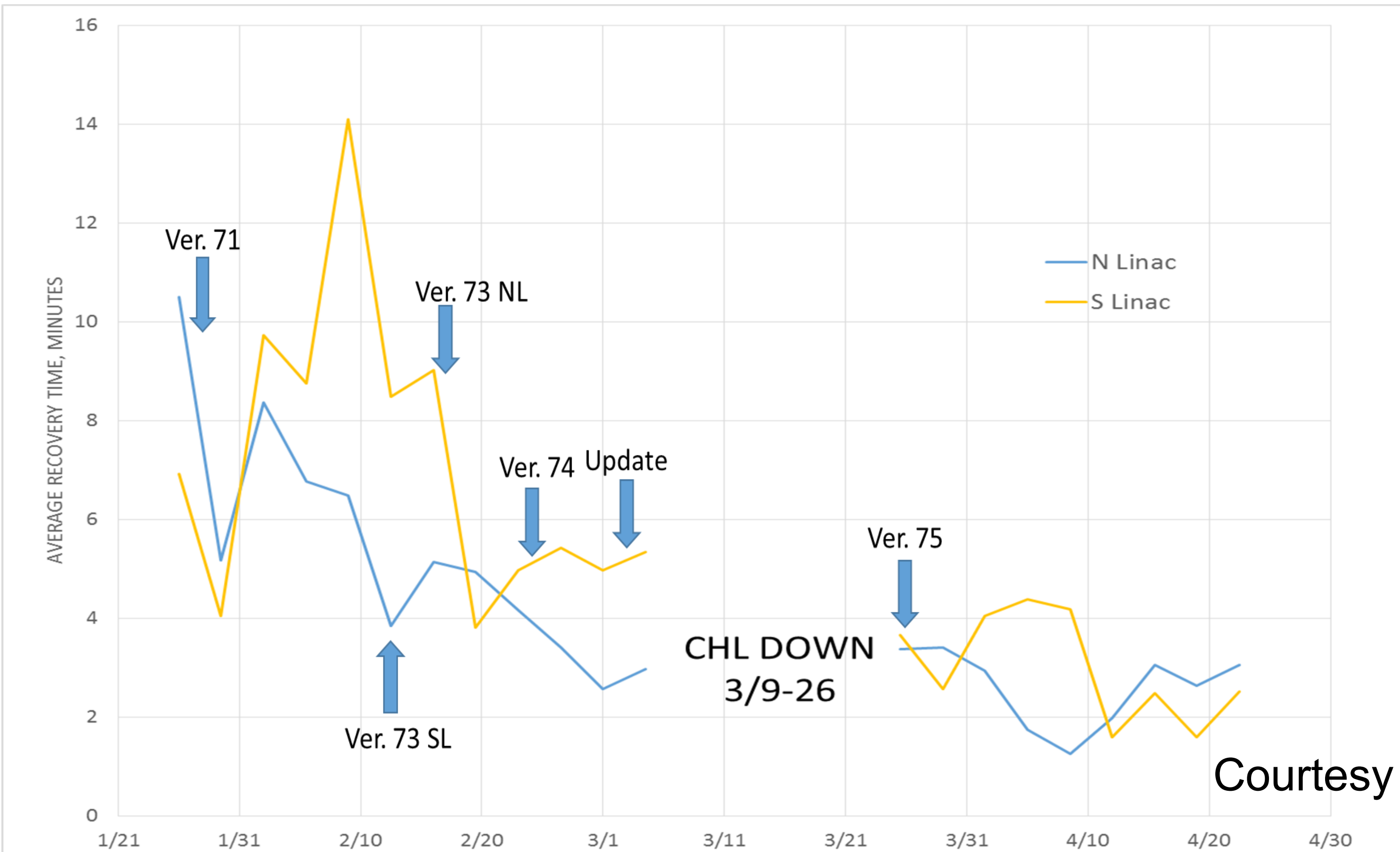


Progress examples – cont'd

- C100 independent cavity heater controls (ENG)
  - Allows finer resolution in heat distribution to mitigate surpassing critical heat flux in the riser – enhanced liquid level stability
  - Can apply Qo vs gradient curvefor more points other than Emax for more precise heat application at the operating gradient set point
- Radiation monitors installed over the C100 zones to track field emission in real time.
- Cryomodule temperature diode display developed facilitate internal temperature monitoring
- Installed higher capability heater power supplies in the C50 zones to allow higher operational gradient values
- Contract for klystrons awarded to replace aging tubes

C100 Recovery Time vs Time

- Controls refinements
  - Algorithms developed to considerably shorten recovery time for tripped C100 cavities
  - Waveform analysis tools developed for fast transient display



Courtesy Bob Legg

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Summary

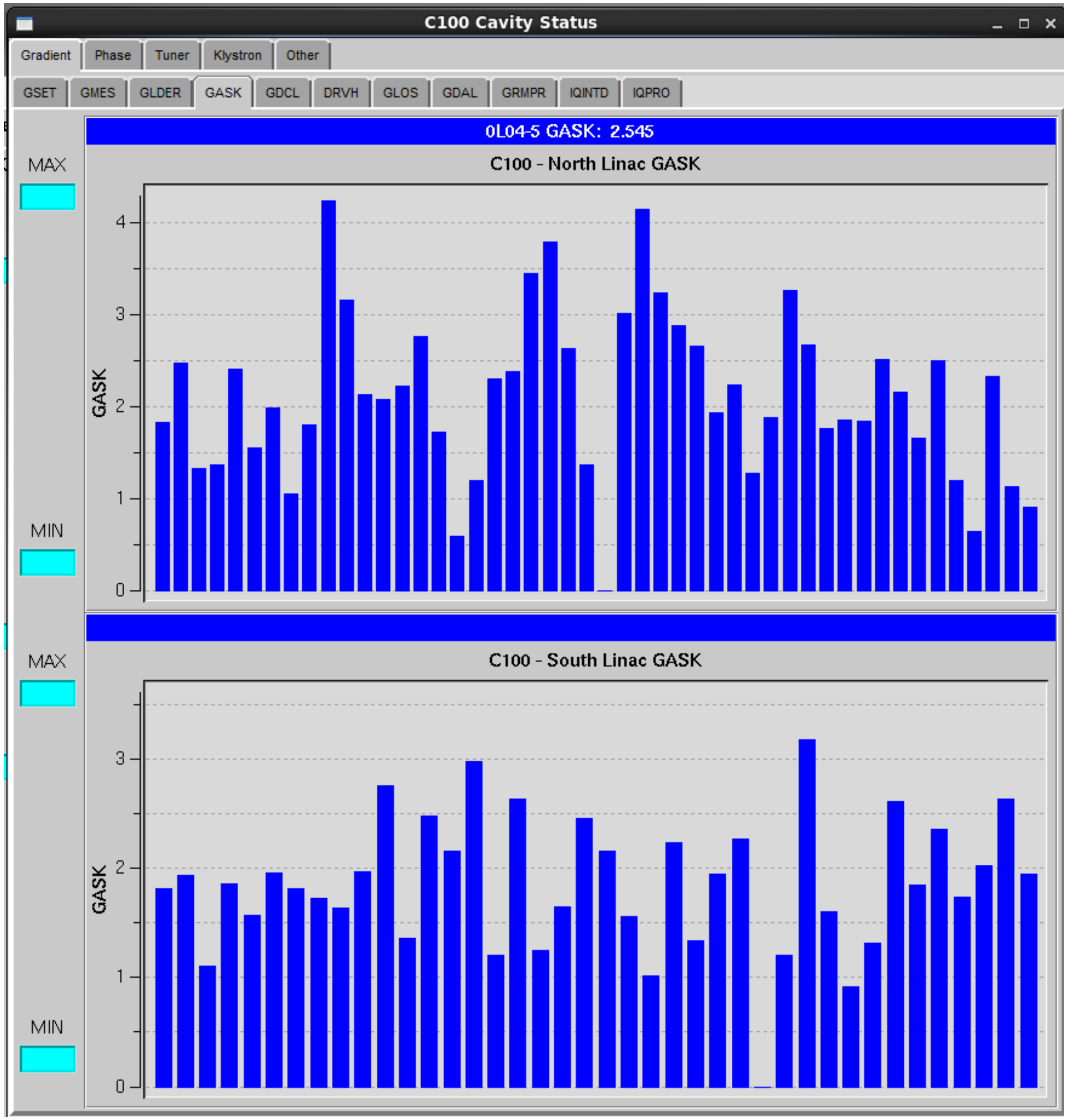
- Gradient management is a complex task for a dynamic gradient delivery system in a CW machine
- The collaboration between divisions and buy-in from management were crucial to the teams progress
- Over 70 issues were identified and prioritized by the team
- Operational gradient gains have been modest as of yet, but machine availability has improved – we are in the process of optimizing C100 gradients at this time
- Process improvement is continuous, and we are making progress.

Acknowledgments

- I'd like to thank the Gradient Improvement Team members for their contributions
  - Ken Baggett, Jay Benesch, Bob Legg, Michael McCaughan, Dave Gelhaar, Mike Drury, Charlie Reece, Nusair Hassan, Ramakrishna Bachimanchi, Adam Carpenter, Tomasz Plawski and Krystina Serafini, whose willingness to share their respective experiences and expertise established a viable vehicle for continued success

Questions, Comments?

Thank you for your time...



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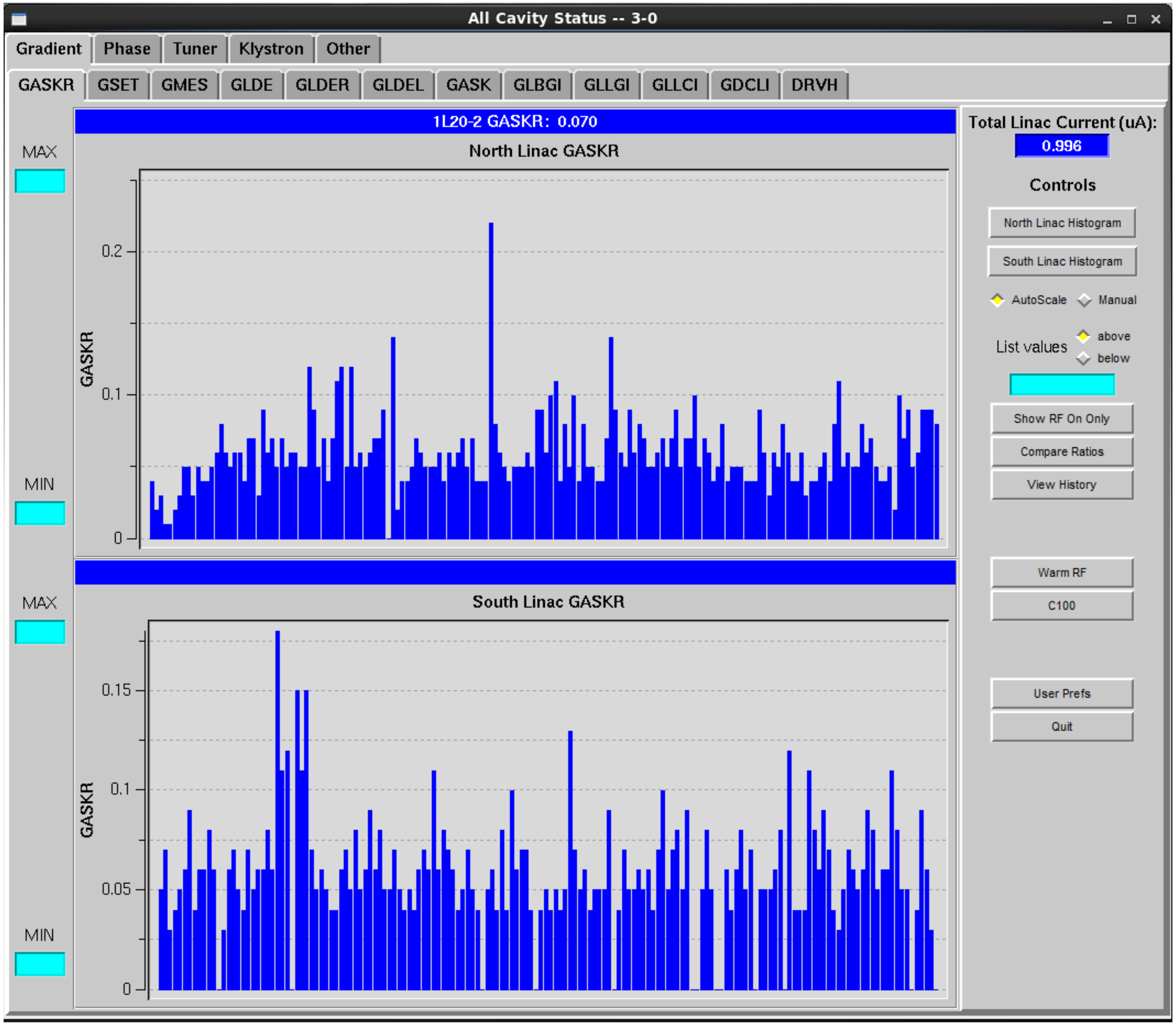
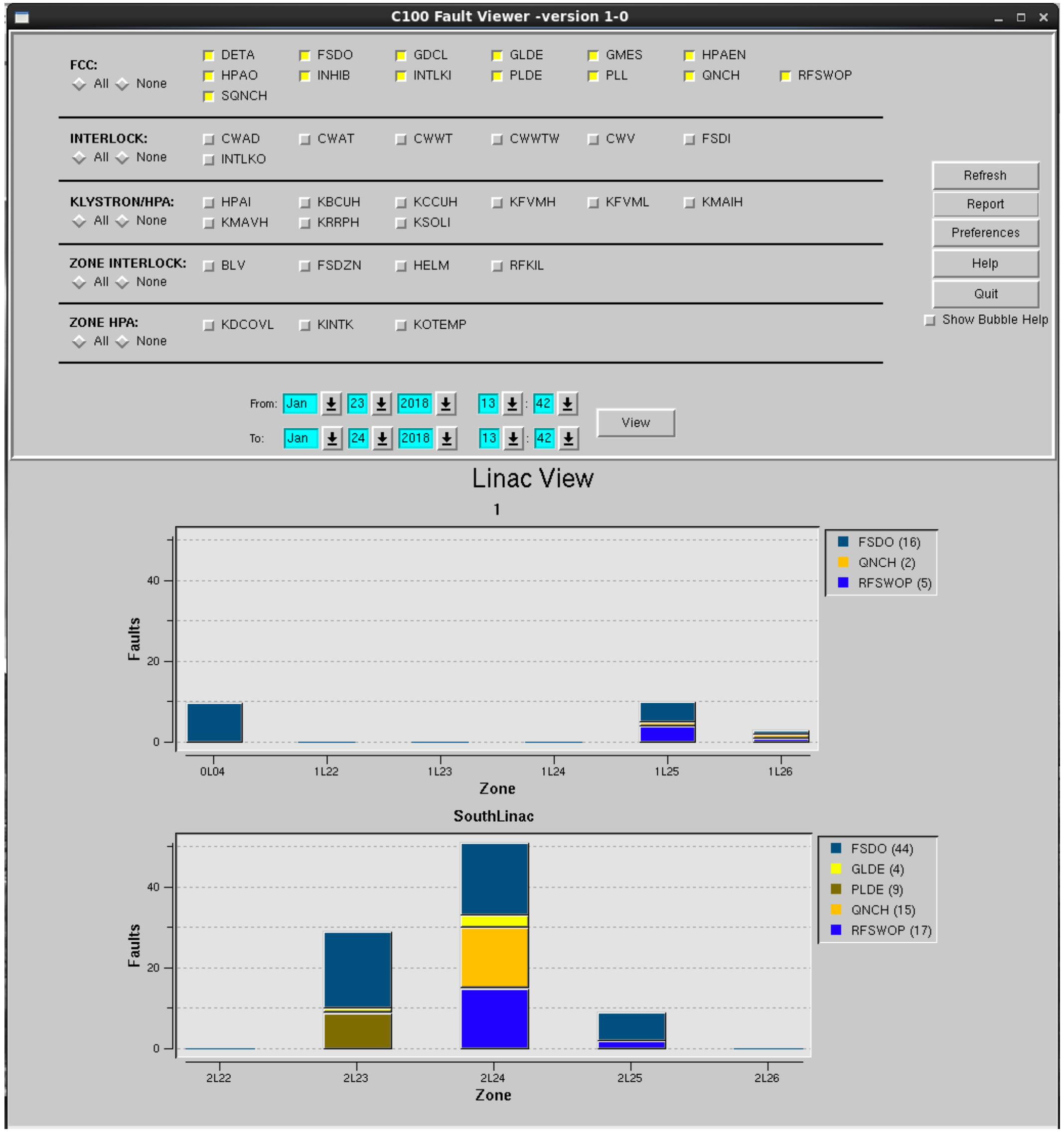


All Cavity Status -- 3-0
Gradient
Phase
Tuner
Klystron
Other
GASKR
GSET
GMES
GLDE
GLDER
GLDEL
GASK
GLBGI
GLLGI
GLLCI
GDCLI
DRVH
1L20-2 GASKR: 0.070
North Linac GASKR
South Linac GASKR
GASKR
MAX
MIN
Total Linac Current (uA):
0.996
Controls
North Linac Histogram
South Linac Histogram
AutoScale
Manual
List values
above
below
Show RF On Only
Compare Ratios
View History
Warm RF
C100
User Prefs
Quit



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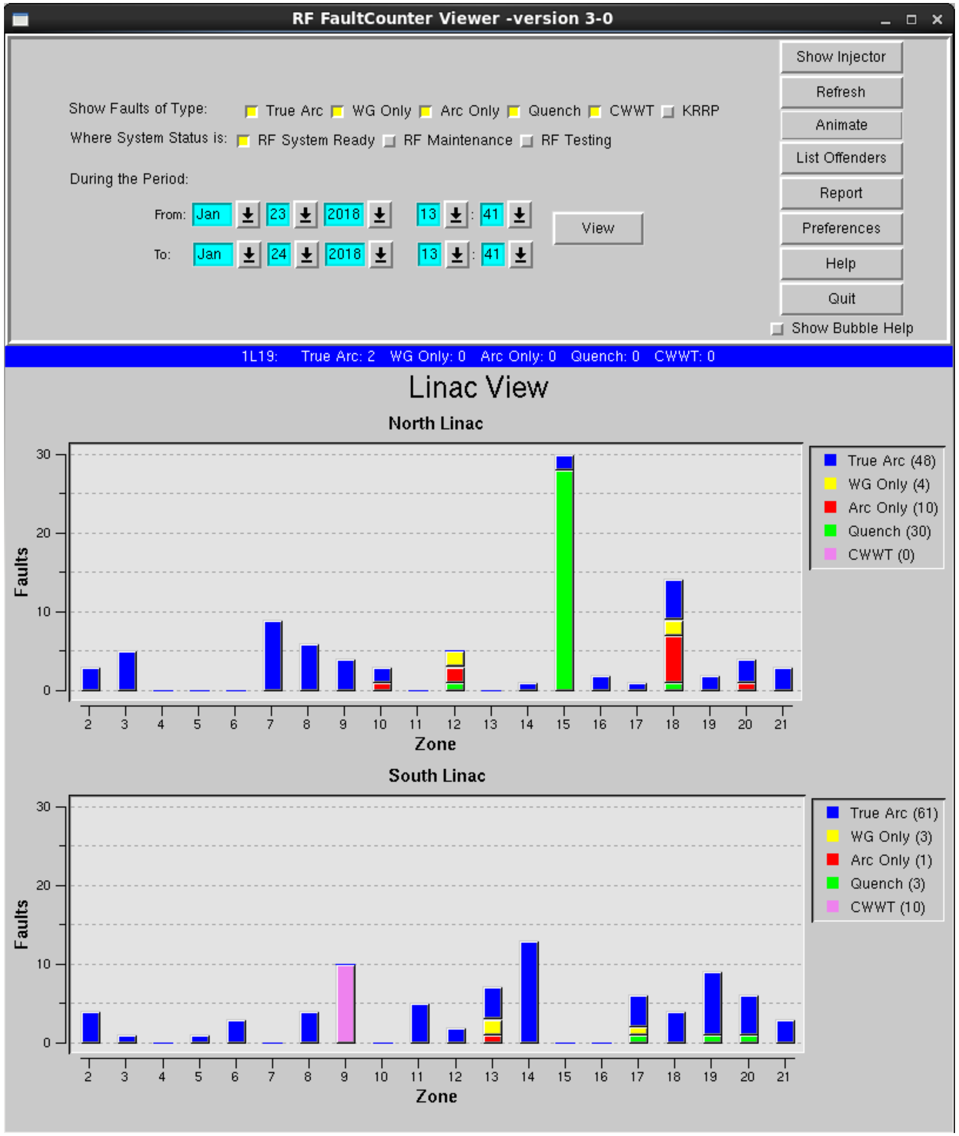

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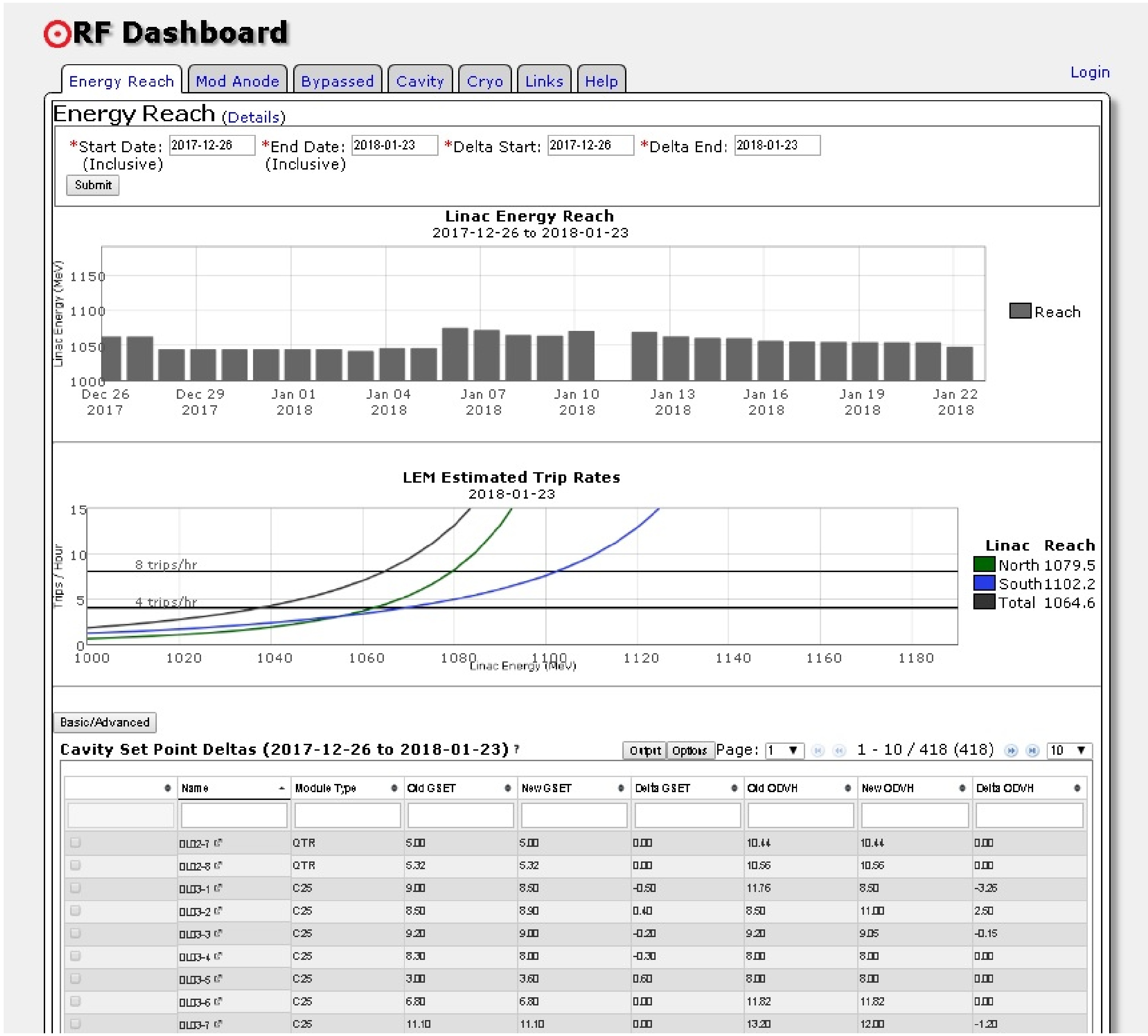
Gradient Improvement Team



	Name	Module Type	Old GSET	New GSET	Delta GSET	Old ODVH	New ODVH	Delta ODVH
	0L02-7	QTR	5.00	5.00	0.00	10.44	10.44	0.00
	0L02-8	QTR	5.32	5.32	0.00	10.56	10.56	0.00
	0L03-1	C25	9.00	8.50	-0.50	11.76	8.50	-3.26
	0L03-2	C25	8.50	8.90	0.40	8.50	11.00	2.50
	0L03-3	C25	9.20	9.00	-0.20	9.20	9.05	-0.15
	0L03-4	C25	8.30	8.00	-0.30	8.00	8.00	0.00
	0L03-5	C25	3.00	3.60	0.60	8.00	8.00	0.00
	0L03-6	C25	6.80	6.80	0.00	11.82	11.82	0.00
	0L03-7	C25	11.10	11.10	0.00	13.20	12.00	-1.20

Gradient Improvement Team

- Show examples of analysis tools and mitigation graphics

Discussion

- In work
  - Analysis of FE contribution to C100 performance and lifetime
  - Application of lessons learned in future cryomodule development and construction

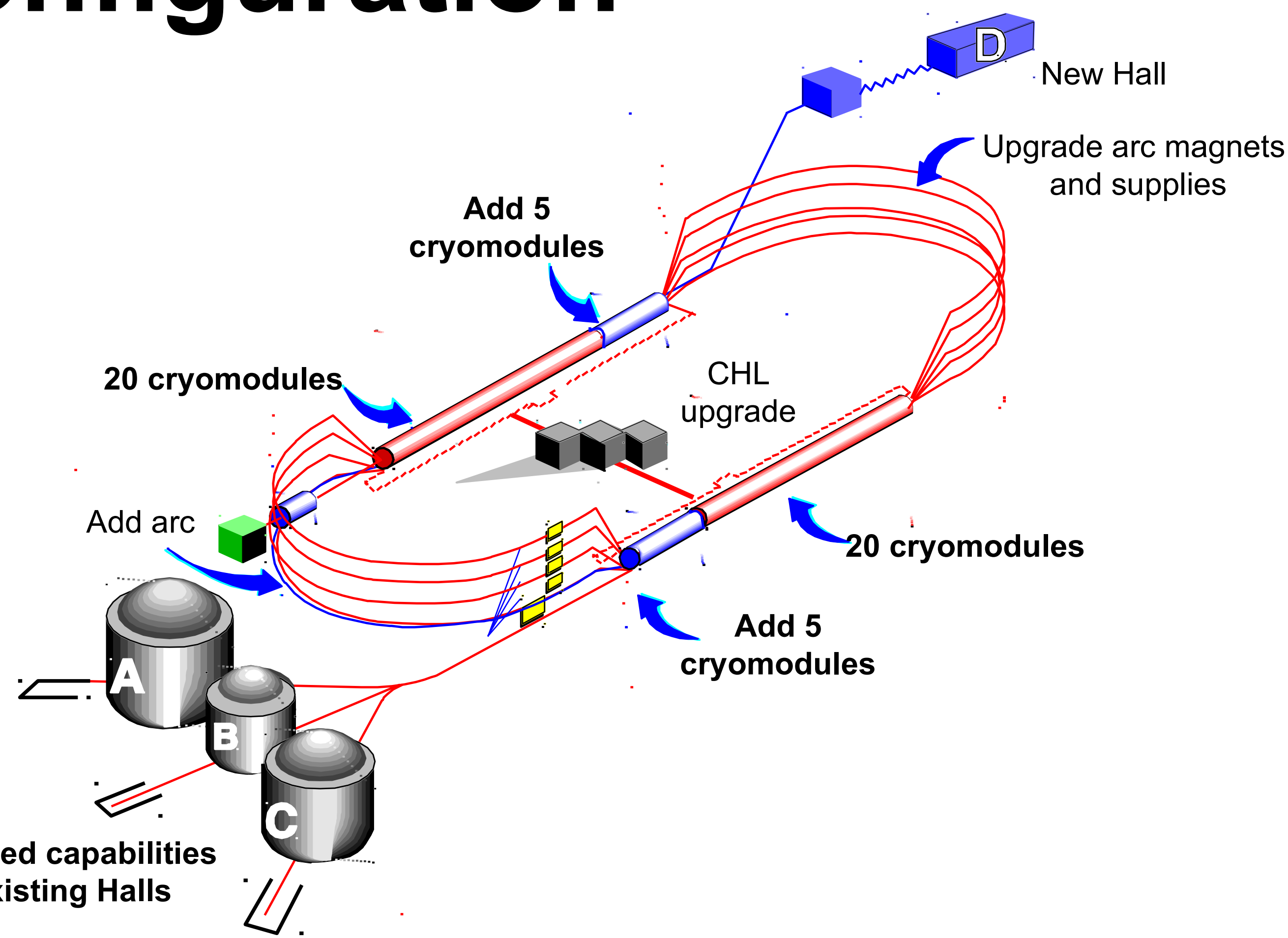
Not So Good Things

- Number of trips and resulting down time
  - Break down into trip types, culminating with quench
  - Mention arc detector degradation, mitigations applied
  - Mention increased radiation and field emission problems
  - Beam line vacuum degradation due to FE (particulates?)
  - Lack of diagnostics to pin point faults (but getting better) Still requires expert intervention to isolate bad cavity
  - Ambiguity into what is actually causing trips…
    - Originally thought to be microphonics as main contributor, but detected “quench” far outnumbers other trips
    - Mention Tom’s “theories”, Rongli particulate contribution
    - Mention and show 1L23 trip reduction after derating by 1 MV/m

Gradient Improvement Team

- Jay Benesch presently handles arc rate models and C100 periodic quench offenders
  - Calculates trip offset and slope for predicting trips
  - Sets MaxGSET in CED for LEM
- Daily analysis and report of gradient reductions
  - Tools being developed to extract information across CED and Cavity History
  - Validate reduction or put into queue for repair/maintenance – can predict maintenance days
- Tools for fault reporting
  - Ops centric, automated if possible…

Jefferson Lab 12 GeV Configuration



Hybrid of 3 Cryomodule Designs

- C20
  - Designed to provide 20 MeV energy gain
  - 5 cell cavity structure
  - Surpassed design expectations
  - Suffers from gradient dependent arc trips
- C50
  - Refurbished C20 modules with structural and cavity treatment improvements to mitigate arc trips and provide 50 MeV of energy gain
- C100
  - New cryomodule design to provide 108 MeV energy gain
  - 7 cell cavity structure
  - Smaller helium vessel
  - New digital RF controls