Cavity String/Cryomodule Cold Test Experience at JLab

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On behalf of Jefferson Lab SRF Team

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U.S. DEPARTMENT OF ENERGY

Jefferson Lab

Work presented in this report are due to the SRF team comprised of all scientific, engineering and technical staff in the SRF Institute

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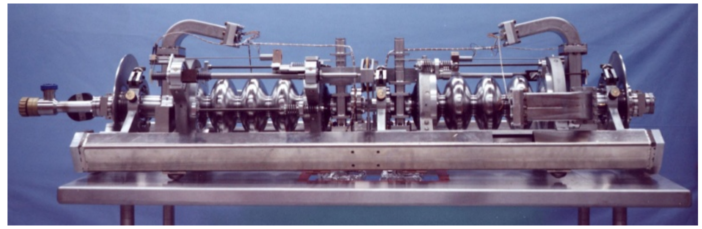
Cavity String/Cryomodule Experience at JLab

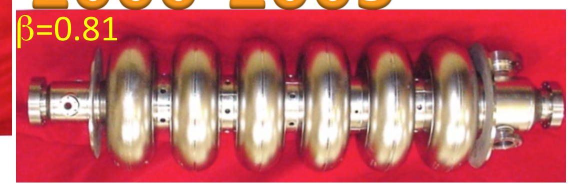
- CEBAF
  - Electron SRF linac, CW
  - 338 cavities
    - 1497 MHz, 5-cell
    - Design Eacc 5 MV/m, $Q0 \geq 2.4\times10^9$
  - 42 cryomodules
  - Re-work 10 modules



1987-1993

- SNS
  - Proton SRF linac, pulsed
  - 81 cavities
    - 805 MHz, 6-cell, $\beta=0.61$ & $\beta=0.81$
    - Design Eacc: 10.2 MV/m ($\beta=0.61$), 15.6 MV/m($\beta=0.81$); $Q0 \geq 5\times10^9$
  - 24 cryomodules

2000-2005

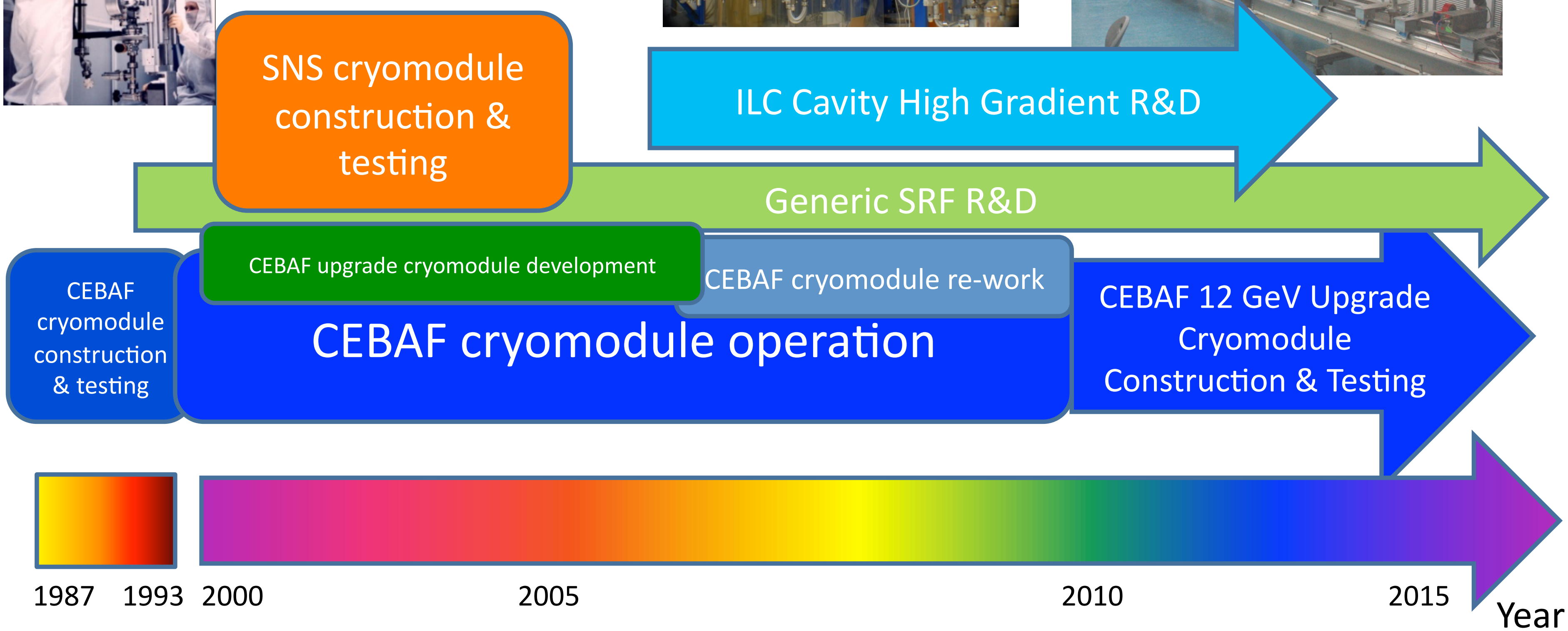


- CEBAF 12 GeV Upgrade
  - Electron SRF linac, CW
  - 80 cavities
    - 1497 MHz, 7-cell
    - Design Eacc 19.2 MV/m, $Q0 \geq 7\times10^9$
  - 10 cryomodules

2010-2015

Large body of experience has been accumulated at JLab in cavity string and cryomodule for CW electron and pulsed proton SRF linacs in past two decades. Analysis of these experience is a worthy effort to success of future SRF projects

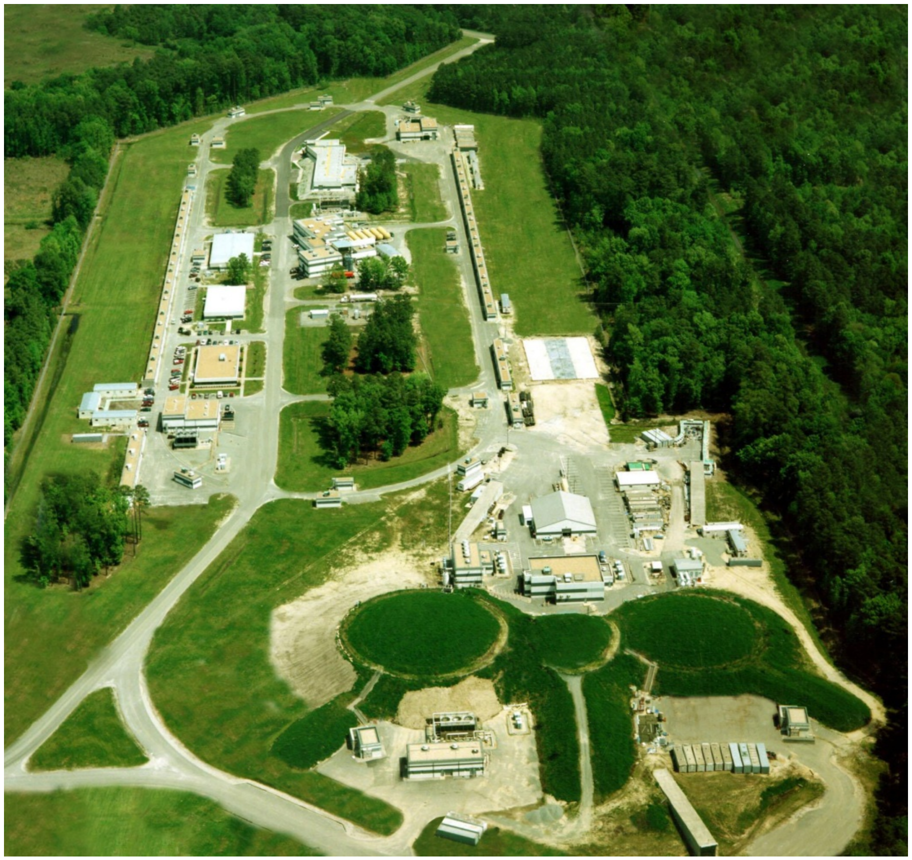
20+ years of cryomodule construction, testing & operation as well as cavity gradient R&D at Jefferson Lab allows advanced SRF technology applicable to many future domestic and international SRF based machines



CEBAF: Continuous Electron Beam Accelerator Facility

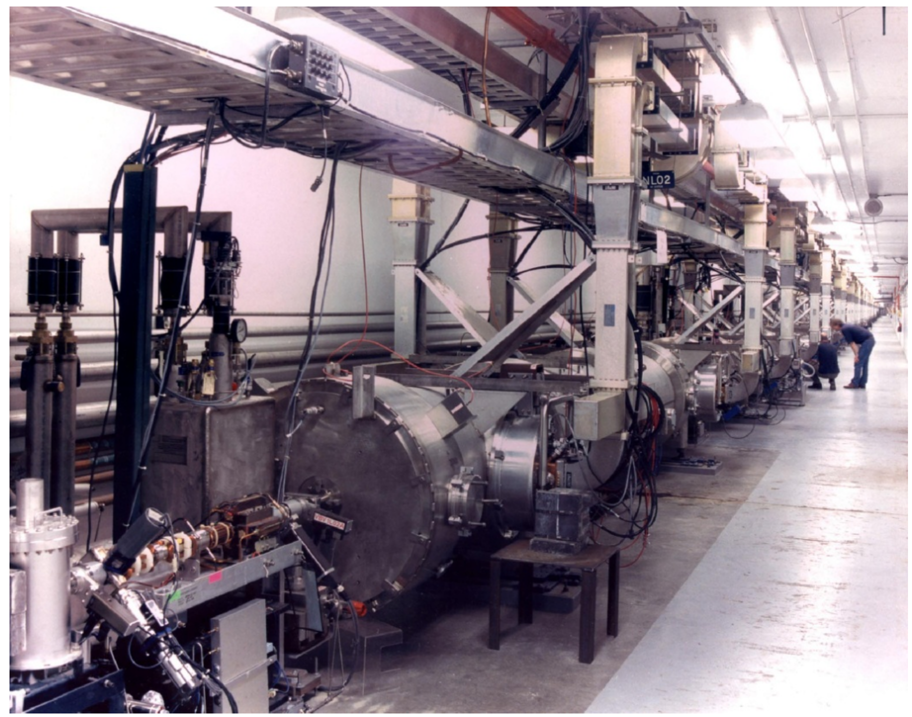
Basic research of atoms's nucleus

Construction 1987-1993
Operation 1994-present



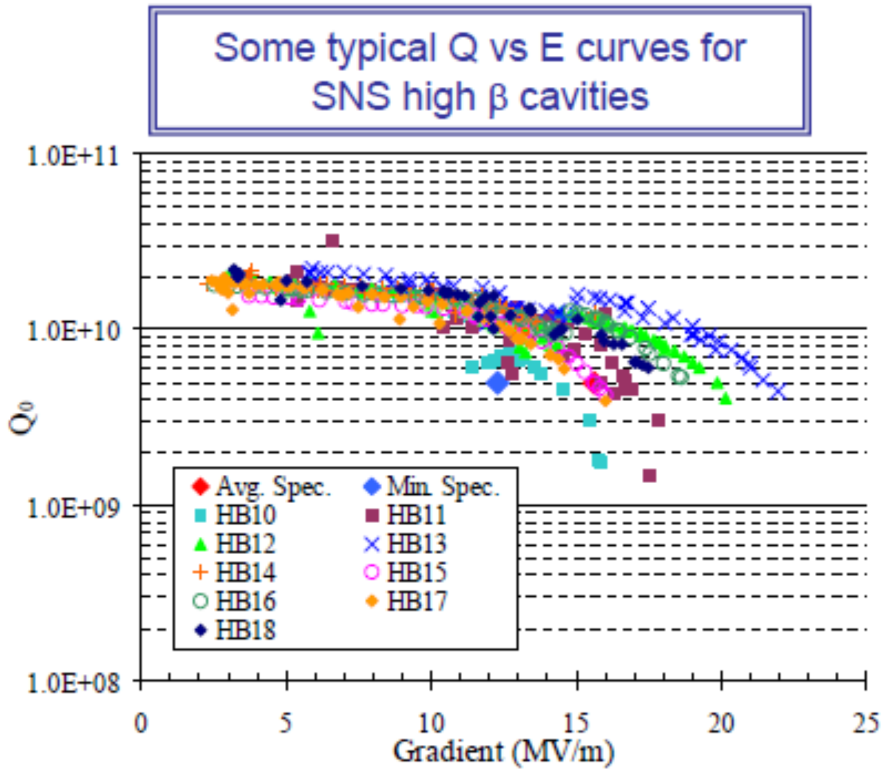
First large-scale application of SRF linac technology

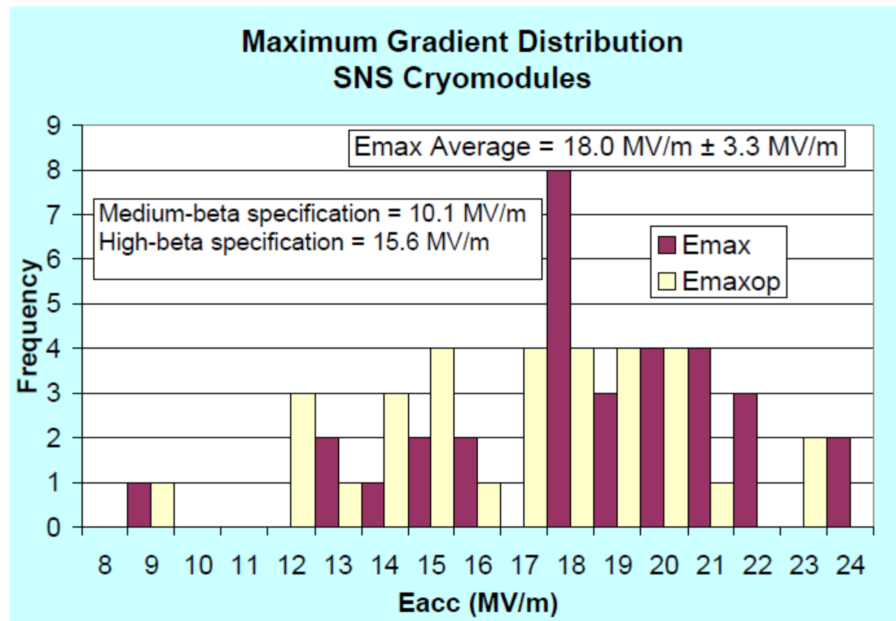
The same SRF technology plus Energy Recovery Linac technology used for JLab's Free Electron Laser



SNS Cryomodule Experience

2000-2005





A predominant limitation of both medium- and high-β cavities was unpredictable stray electron loading due to multipacting/field emission

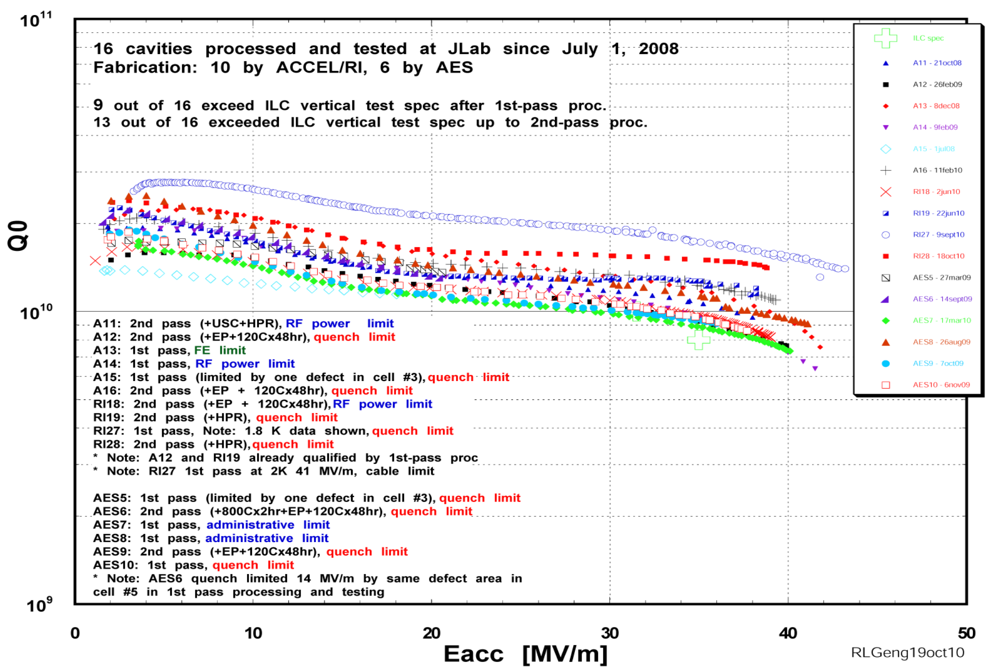
Limitations arising from module cooling issues when all cavities are operated together might impose lower limits

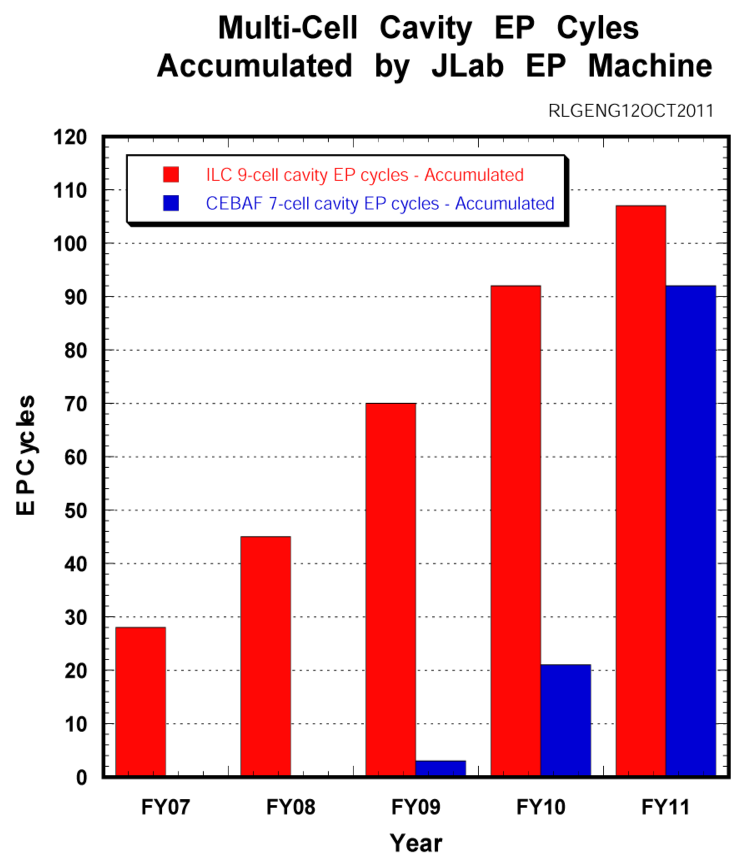
M. Drury et al, PAC2005, p.3496.

ILC Cavity High Gradient R&D:
Reduce field emission, overcome quench limit

Since 2006

Developed repeatable high quality processing and handling procedure for multi-cell cavities

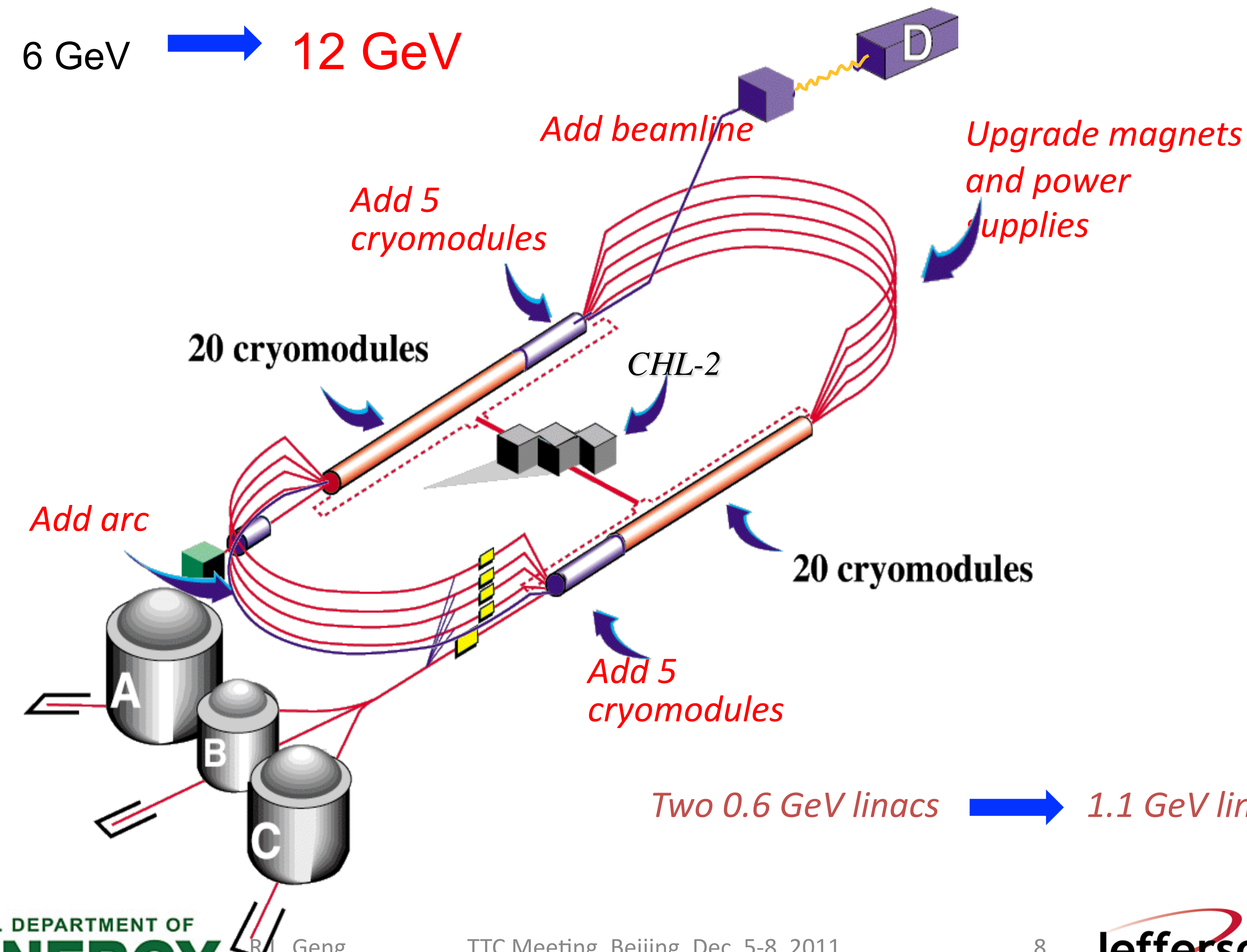




Technology and in-house expertise developed for ILC cavity gradient R&D applied to CEBAF 12 GeV upgrade

CEBAF 12 GeV Upgrade **Presently on-going…**

6 GeV → 12 GeV



Two 0.6 GeV linacs → 1.1 GeV linacs

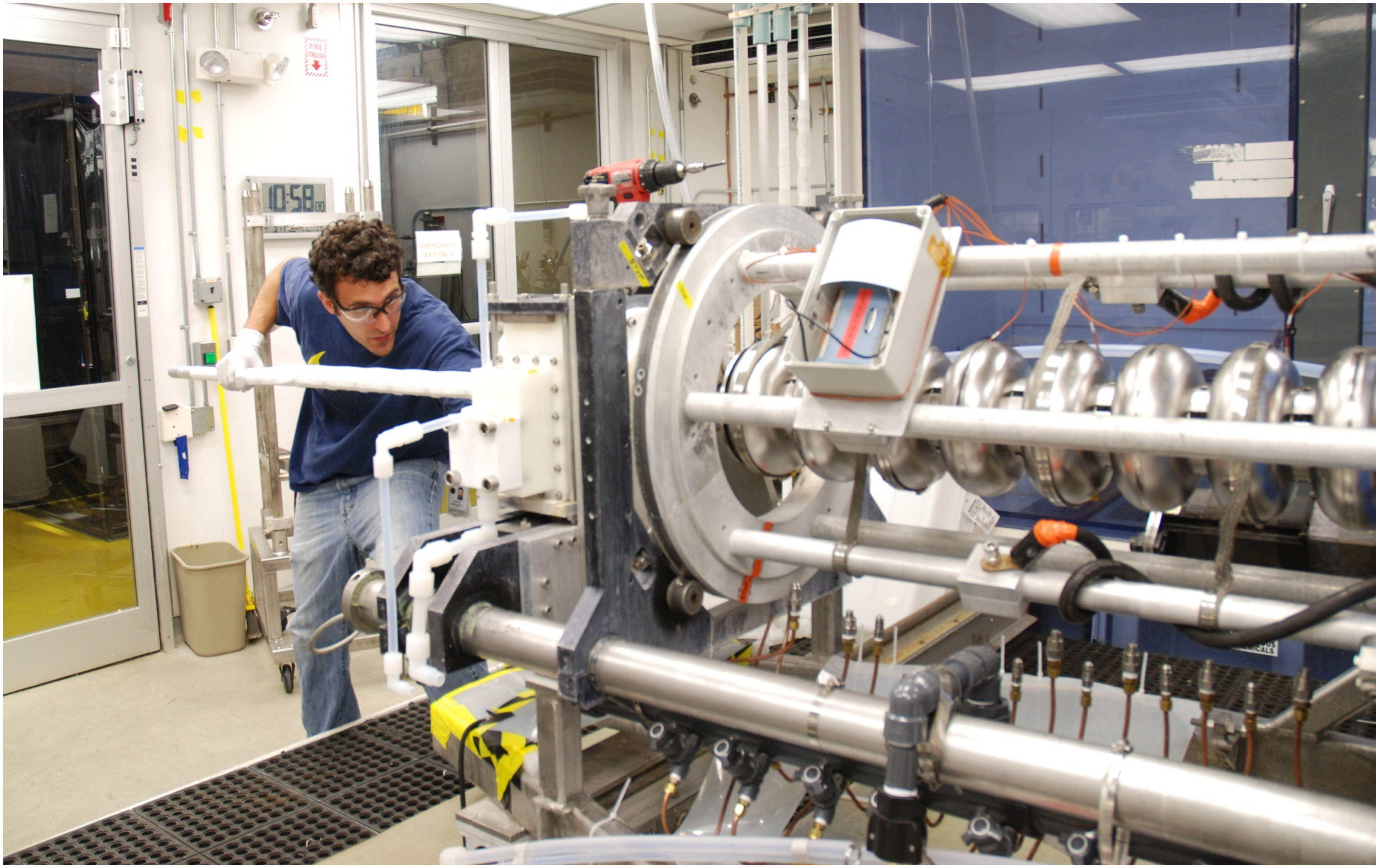
Key Cryomodule Technical Parameters for CEBAF 12 GeV Upgrade Project

- CW operation
- Number of new cryomodules: 10
- Voltage per module: ≥ 108 MV (average)
- Heat budget: ≤ 300 W @ 2.07 K
- Cavity: 1.497 MHz, Low-loss cell shape
- Operating Spec: 19.2 MV/m at $Q_0 > 7\times10^9$ @ 2.07 K
- Cavity length: 1 m (0.7 m active cell length)
- Cryomodule length: 8.5 m
- RF power: 7.5 kW (average)/13 kW (peak)
- Higher Order Mode (HOM) damping
  - Transverse (R/Q)Qk < 2.4×10^{10} Ω/m
  - Longitudinal (R/Q)Q < 6.5×10^{11} Ω

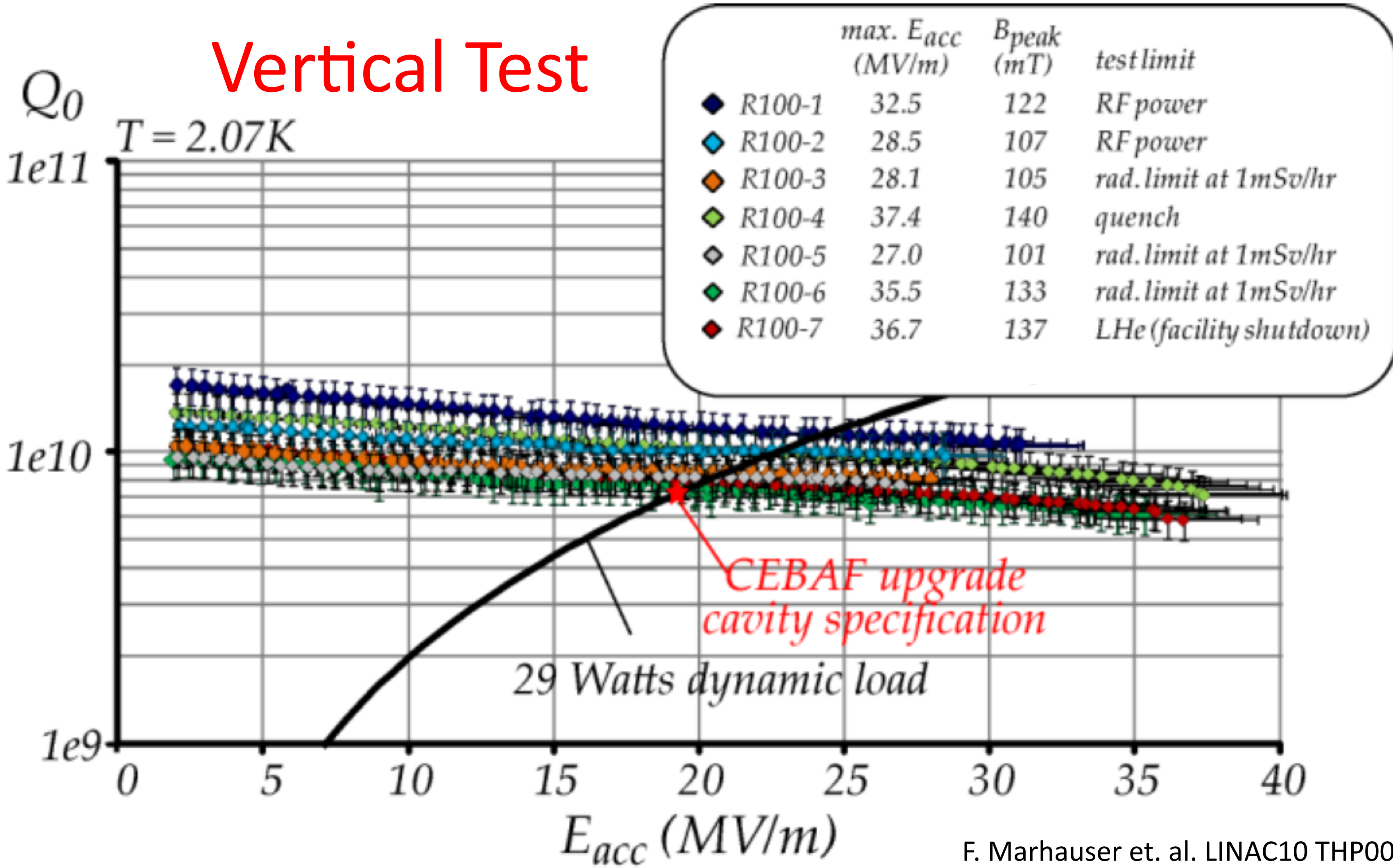
CEBAF 12 GeV Upgrade Cavity and Cavity String Processing and Handling Procedure

- Heavy BCP (160 μm removal) (by vendor)
- Pre-tune (by vendor)
- Receipt inspection – mechanical and RF
- Ultrasonic cleaning
- Vacuum furnace heat treatment (600 °C x 10 hr)
- Light EP (30 μm removal)
- Post-EP cleaning (low pressure rinse + ultrasonic cleaning with detergent)
- Tuning with No-touch bead-pull
- Helium vessel TIG welding
- Flange lapping
- First high pressure water rinse
- First clean room assembly
- Final high pressure water rinse
- Drip dry in class-10 area
- Final clean room assembly
- Slow pump down
- Leak check
- In-situ low temperature bake (120 °C x 24 hr)
- Vertical test for qualification
- High pressure water rinse
- Drip dry in class-10 area
- String assembly in clean room

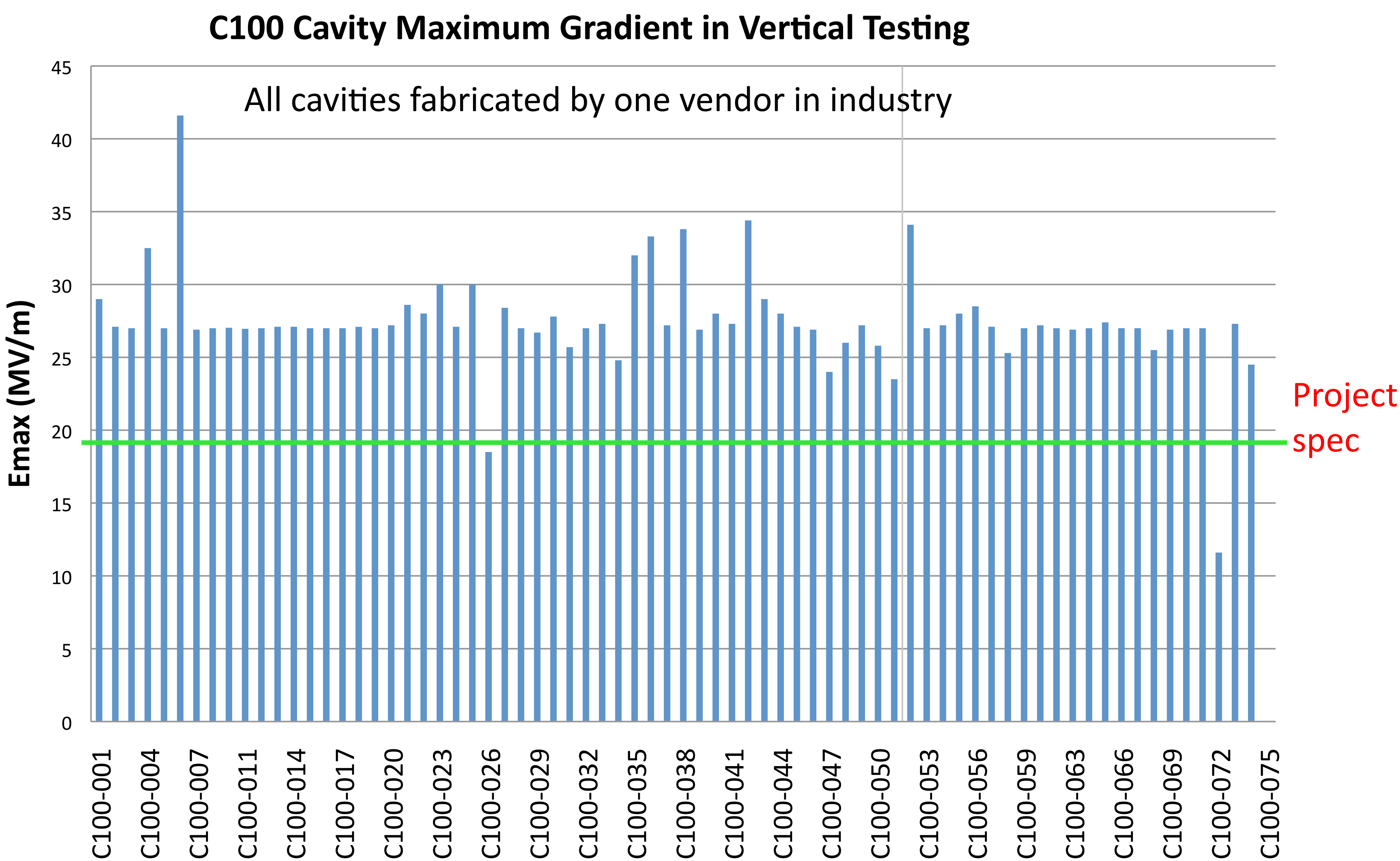
JLab horizontal EP machine



JLab in-house fabricated, in-house processed and tested pre-production 7-cell cavities



F. Marhauser et. al. LINAC10 THP009



C100 Cavity Maximum Gradient in Vertical Testing
All cavities fabricated by one vendor in industry
Emax (MV/m)
45
40
35
30
25
20
15
10
5
0
C100-001
C100-004
C100-007
C100-011
C100-014
C100-017
C100-020
C100-023
C100-026
C100-029
C100-032
C100-035
C100-038
C100-041
C100-044
C100-047
C100-050
C100-053
C100-056
C100-059
C100-063
C100-066
C100-069
C100-072
C100-075
Project spec

Comparison of Gradient Yield: CEBAF vs. ILC Cavities Processes & Tested at JLab

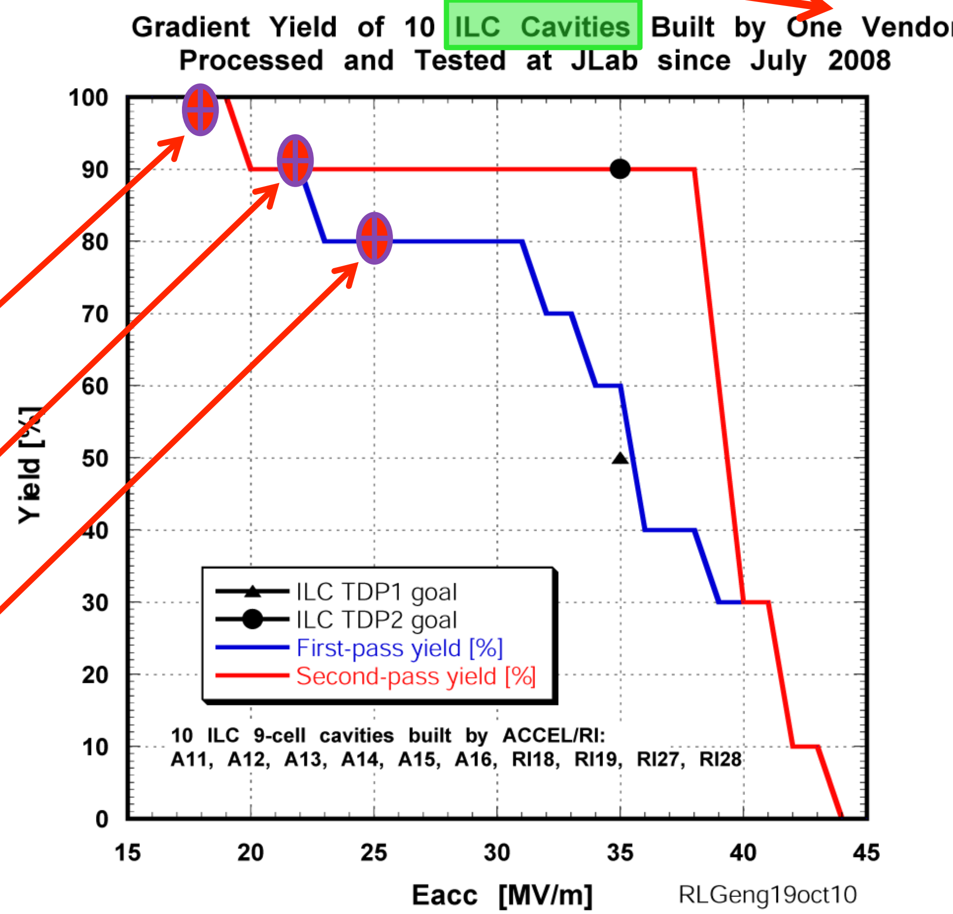
CEBAF 7-cell: Bulk chemistry by BCP + 600Cx10hr + Light EP + 120Cx24hr; ILC 9-cell at JLab: Bulk chemistry by EP + 800Cx2hr + Light EP + 120Cx48hr

C100 Cavity Gradient Yield Drop due to Quench Limit

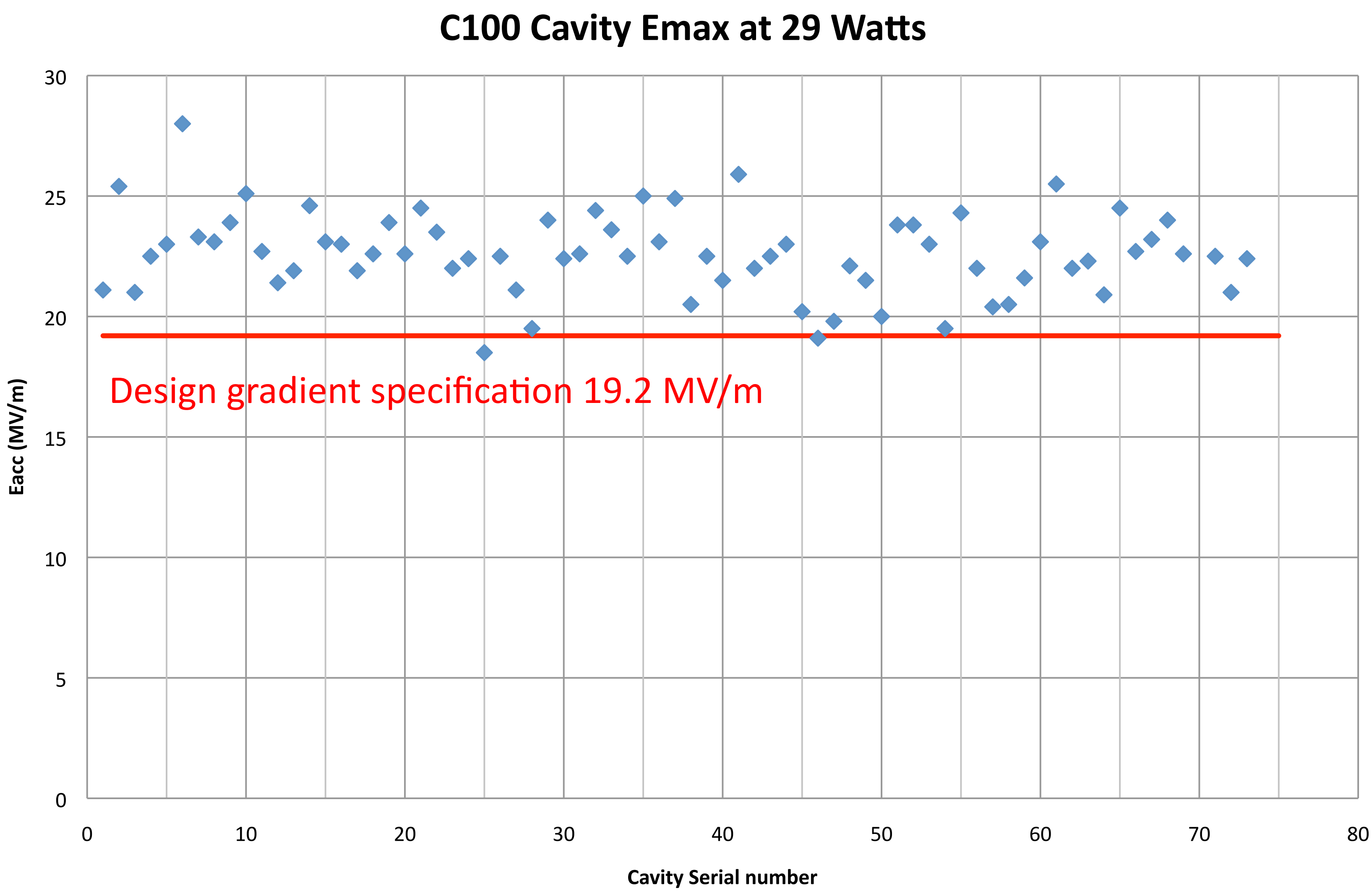
74 CEBAF 7-cell cavities fabricated by one vendor

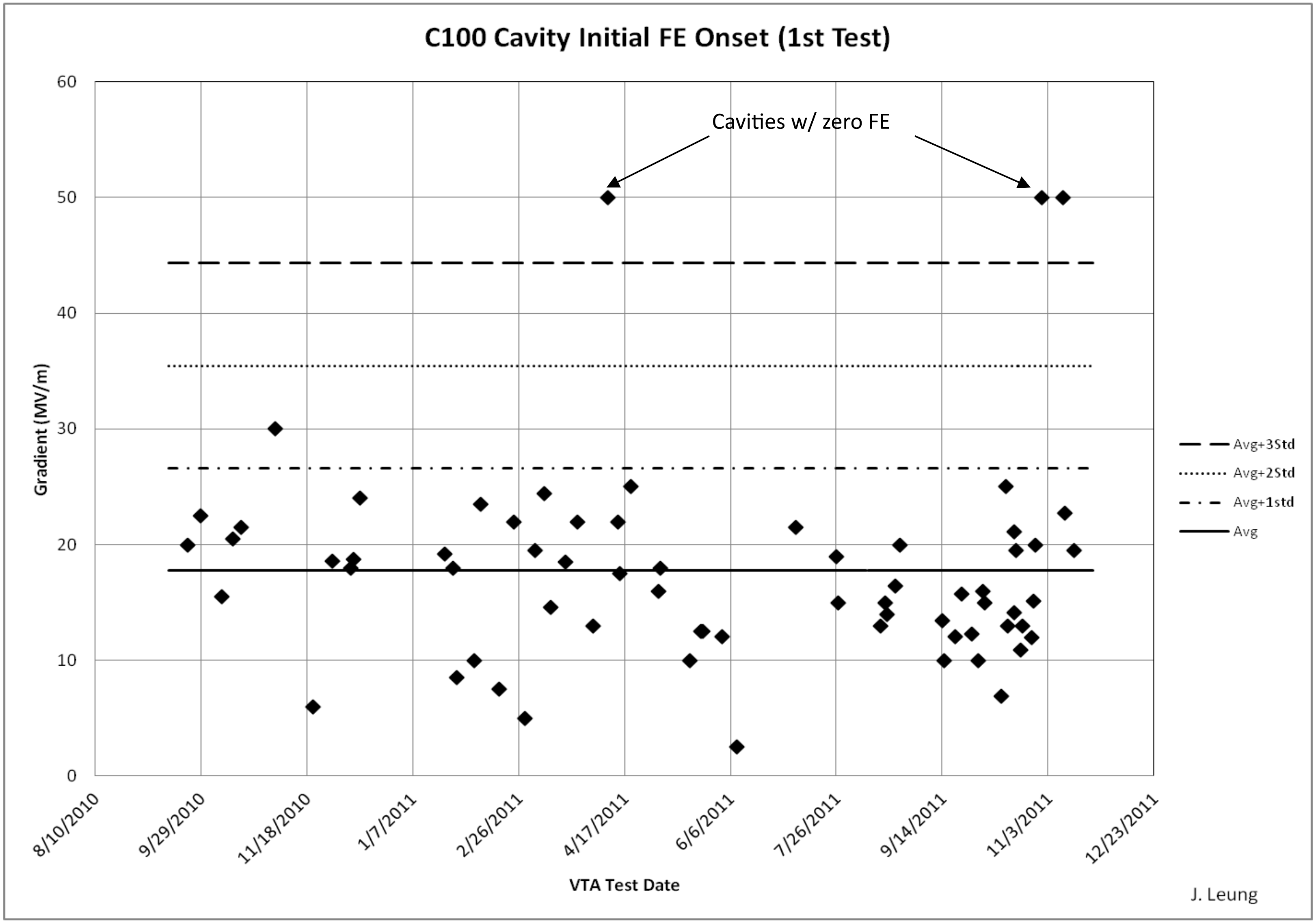
Same vendor

Eacc [MV/m]	Yield [%]	Hpk [Oe]	Corresponding Eacc for TTF shape for ILC [MV/m]
≥15	99	561	13
≥20	97	748	18
≥25	92	935	22
≥28.5	80*	1066	25

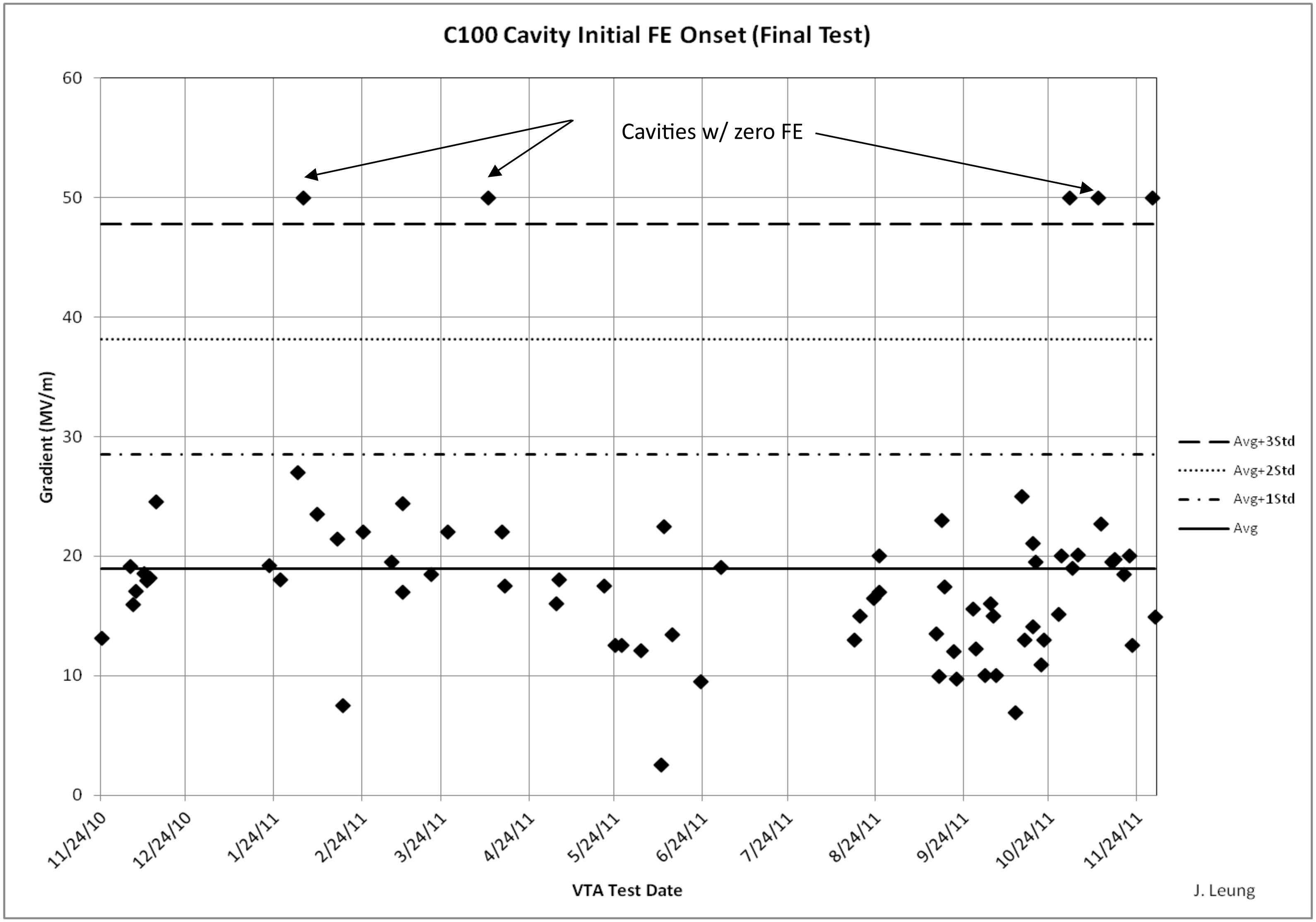


* Optimistic estimation due to administrative limit at 27 MV/m for some cavity testing

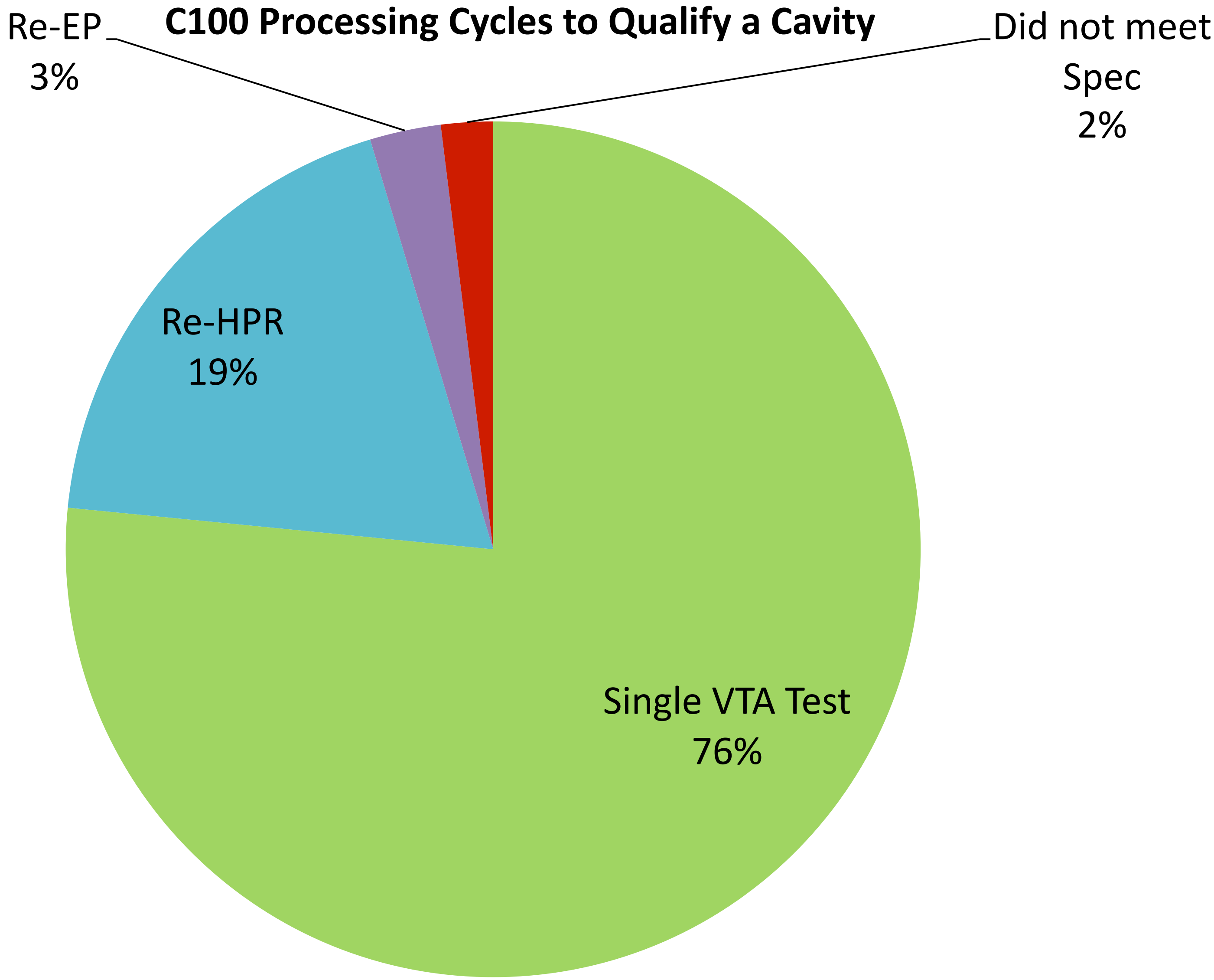

C100 Cavity Emax at 29 Watts
30
25
20
15
10
5
0
Eacc (MV/m)
Design gradient specification 19.2 MV/m
0
10
20
30
40
50
60
70
80
Cavity Serial number



C100 Cavity Initial FE Onset (1st Test)
Cavities w/ zero FE
Gradient (MV/m)
0
10
20
30
40
50
60
8/10/2010
9/29/2010
11/18/2010
1/7/2011
2/26/2011
4/17/2011
6/6/2011
7/26/2011
9/14/2011
11/3/2011
12/23/2011
VTA Test Date
Avg+3Std
Avg+2Std
Avg+1std
Avg
J. Leung


C100 Cavity Initial FE Onset (Final Test)
Cavities w/ zero FE
Gradient (MV/m)
60
50
40
30
20
10
0
11/24/10
12/24/10
1/24/11
2/24/11
3/24/11
4/24/11
5/24/11
6/24/11
7/24/11
8/24/11
9/24/11
10/24/11
11/24/11
VTA Test Date
Avg+3Std
Avg+2Std
Avg+1Std
Avg
J. Leung

C100 Processing Cycles to Qualify a Cavity

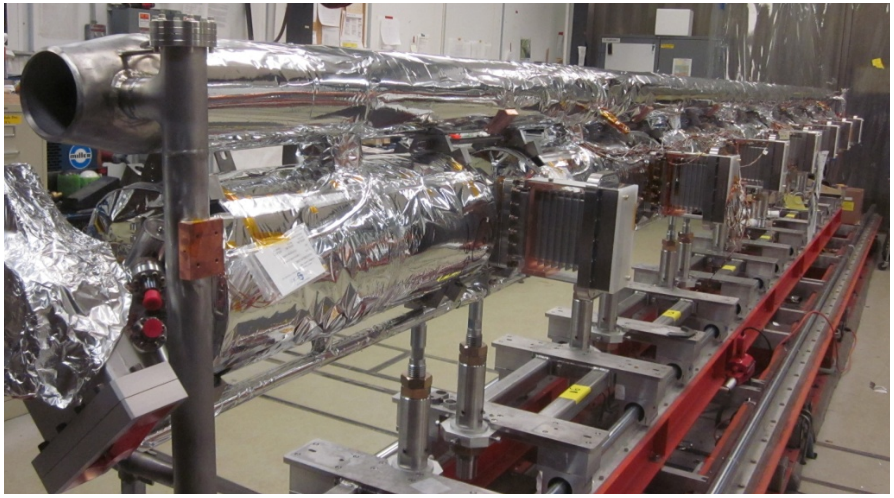


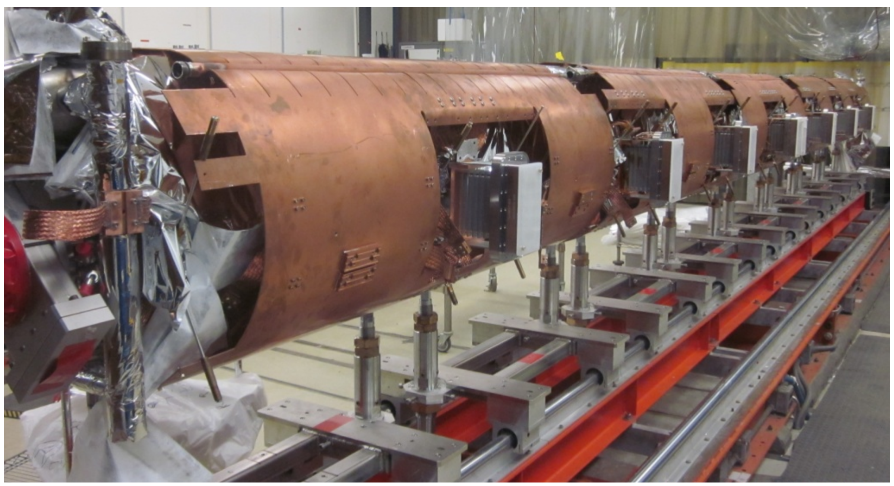
Cavity string assembly area in Class-100 Clean room at Jefferson Lab

Assembled medium beta cavity string for SNS

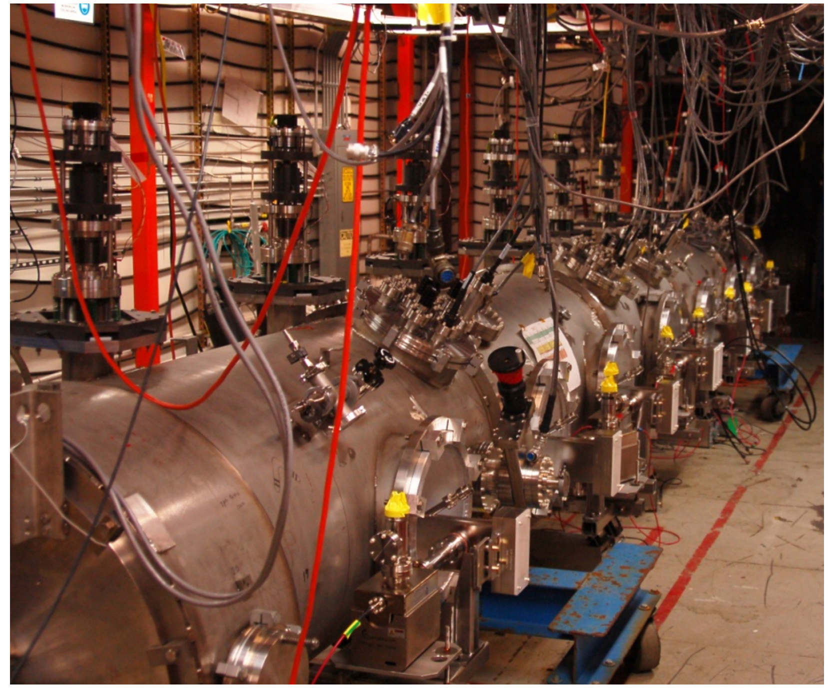
Assembled cavity string for CEBAF 12 GeV upgrade

Cryomodule Assembly and Testing in CMTF at JLab



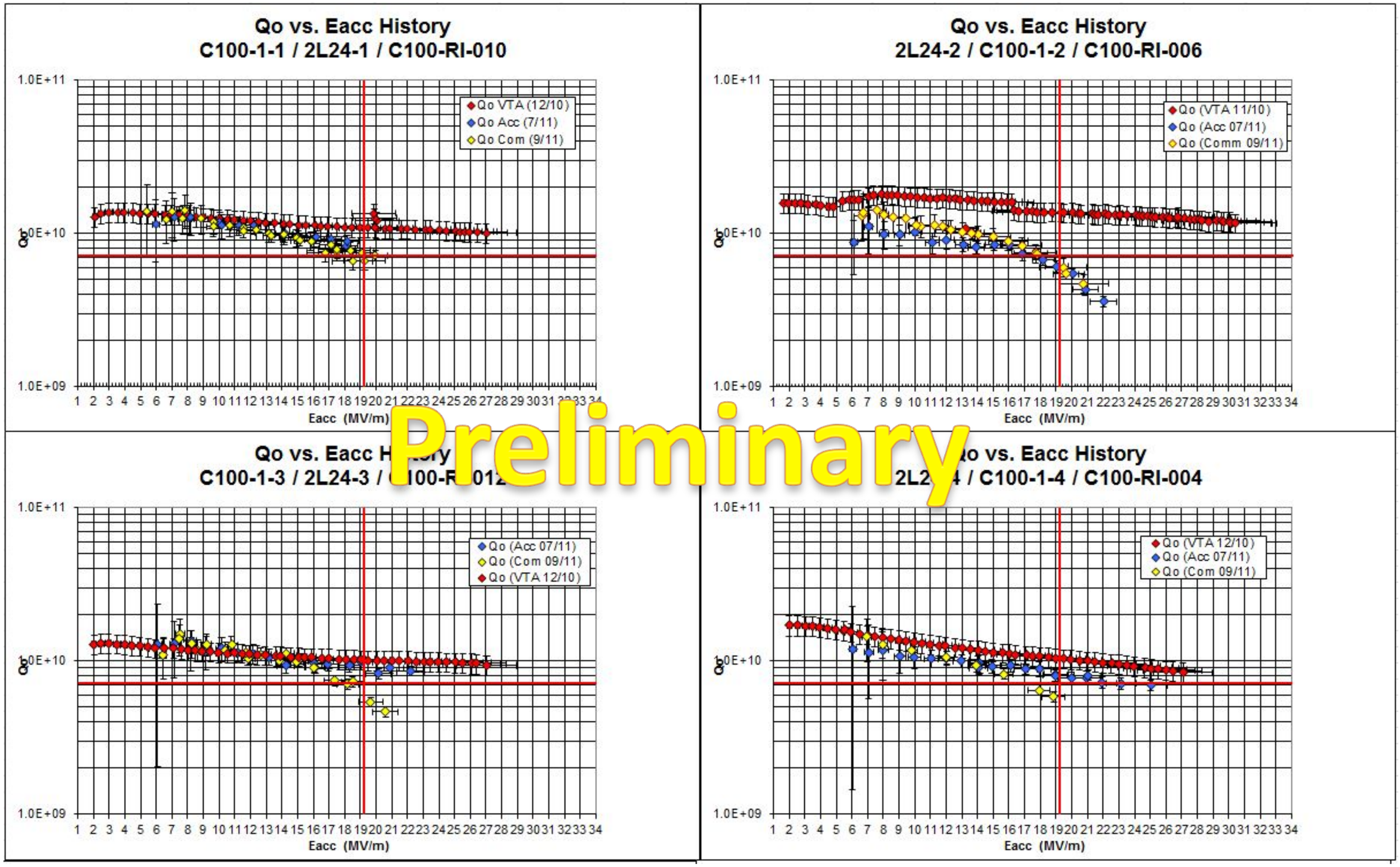


Cryomodule Assembly at JLab

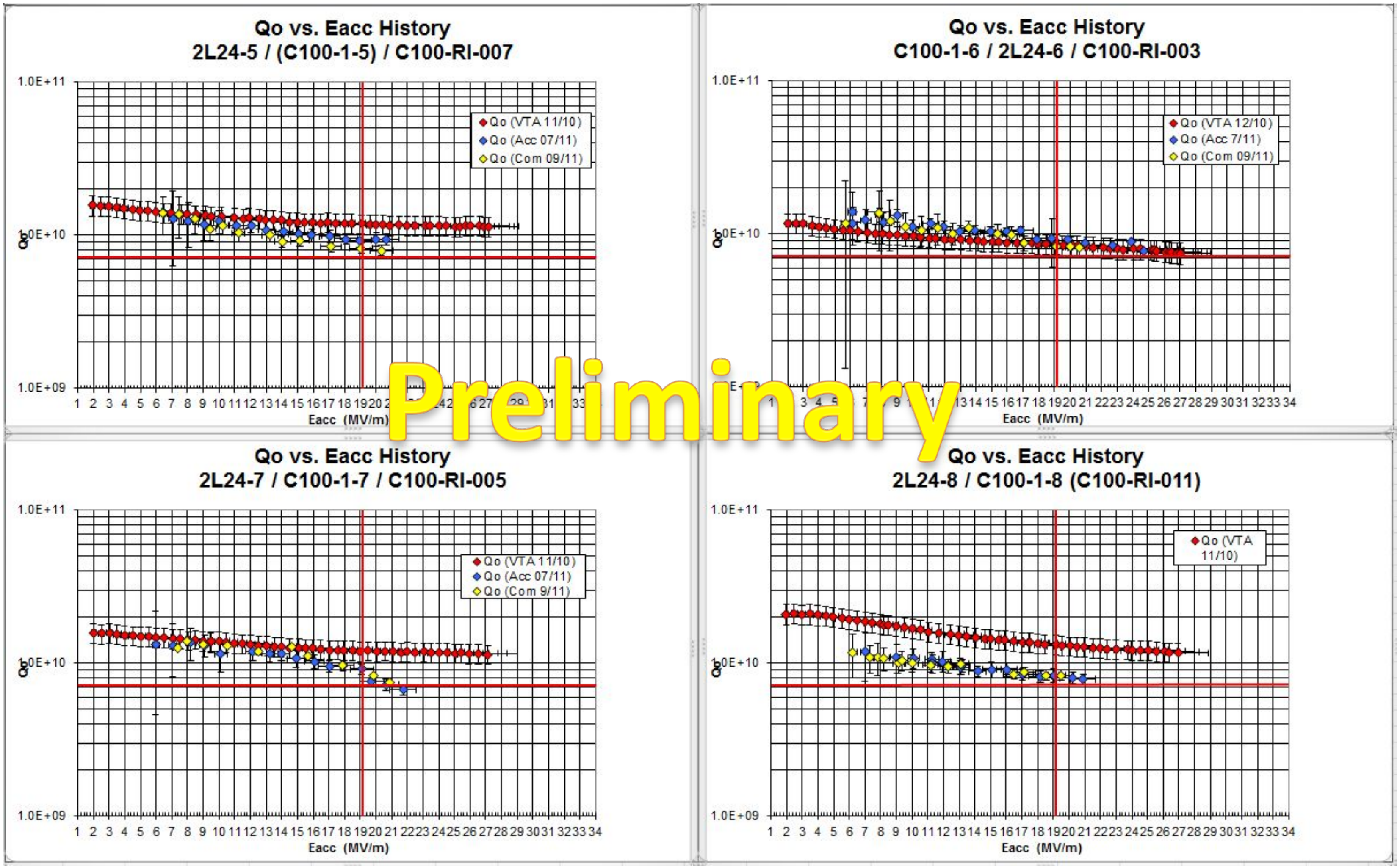


- 300 W helium refrigerator
- 21 m x 7 m with radiation shielding
- Magnetically shielded
- Dedicated control room

C100-1 Qo vs. E Measurement History Cavities 1-4



C100-1 Qo vs. E Measurement History Cavities 5-8



C100-1 CMTF Testing vs. VTA Testing

Cavities in cryomodue C100-1 all meet or exceed CEBAF 12 GeV upgrade project spec
Understanding change of Emax and FE onset from VTA to CMTF testing is worthy effort and under way (more later)

Preliminary

Cavity	VTA Final Emax [MV/m]	VTA Final Limit	CMTF Emax (MV/m)	CMTF Limit	CMTF FE Onset (MV/m)	VTA FE Onset [MV/m]
1	27.0	admin	21.6	Thermal	19.9	18.0
2	30.4	admin	22.4	Thermal	11.6	13.0
3	27.0	admin	22.3	Thermal	22.0	18.7
4	27.1	admin	25.4	Thermal	N/A	18.5
5	26.5	admin	21.0	Thermal	18.5	18.3
6	27.1	admin	25.8	Thermal	19.0	18.7
7	27.2	admin	22.2	Thermal	13.0	20.0
8	27.0	admin	21.5	Thermal	15.2	24.0

C100-2 CMTF Testing vs. VTA Testing

Cavities in cryomodue C100-2 all meet or exceed CEBAF 12 GeV upgrade project spec
Understanding change of Emax and FE onset from VTA to CMTF testing is worthy effort and under way (more later)

Preliminary

Cavity	VTA Final Emax [MV/m]	VTA Final Limit	CMTF Emax (MV/m)	CMTF Limit	CMTF FE Onset (MV/m)	VTA FE Onset [MV/m]
1	27.1	admin	21.8	Thermal	N/A	23.5
2	27.0	admin	24.0	Thermal	N/A	NO FE
3	27.1	admin	21.3	Thermal	N/A	NO FE
4	27.0	admin	21.9	Thermal	N/A	NO FE
5	27.0	admin	20.0	Thermal	N/A	NO FE
6	27.2	admin	21.4	Thermal	N/A	19.5
7	N/A	N/A	19.8	Thermal	N/A	N/A
8	27.0	admin	19.5	Thermal	N/A	NO FE

C100-3 CMTF Testing vs. VTA Testing

Cavities in cryomodue C100-3 all meet or exceed CEBAF 12 GeV upgrade project spec
Understanding change of Emax and FE onset from VTA to CMTF testing is worthy effort and under way (more later)

Preliminary

Cavity	VTA Final Emax [MV/m]	VTA Final Limit	CMTF Emax (MV/m)	CMTF Limit	CMTF FE Onset (MV/m)	VTA FE Onset [MV/m]
1	N/A	N/A	23.7	Thermal	17.9	N/A
2	25.7	Quench	21.7	Thermal	N/A	NO FE
3	28.6	FE	25.0	Admin	16.8	17.0
4	27.1	Admin	22.9	Thermal	N/A	19.2
5	28.0	FE	21.6	Thermal	14.0	24.4
6	27.8	Quench	24.9	Thermal	11.0	NO FE
7	N/A	N/A	22.2	Thermal	N/A	N/A
8	27.0	admin	24.5	Thermal	N/A	22.0

	CEBAF	SNS	CEBAF Upgrade
CW	Y		Y
Pulsed		Y	
Frequency [MHz]	1497	805	1497
Cavity cell #	5	6	7
# of cavities	320	81	80
Epk/Eacc	2.56	2.71(β=0.61) 2.19(β=0.81)	2.17
Hpk/Eacc [Oe/(MV/m)]	45.6	57.2(β=0.61) 47.2(β=0.81)	37.4
Operating gradient [MV/m]	≥5	10.2(β=0.61) 15.6(β=0.81)	17.5 (average)
Q0	$\geq 2.4\times10^9$	$\geq 5\times10^9$	$\geq 7\times10^9$
Operating Temp. [K]	2.07	2.1	2.07
Epk [MV/m]	≥12.8	27.6(β=0.61) 34.2(β=0.81)	41.7
Hpk [Oe]	≥228	580(β=0.61) 732(β=0.81)	718

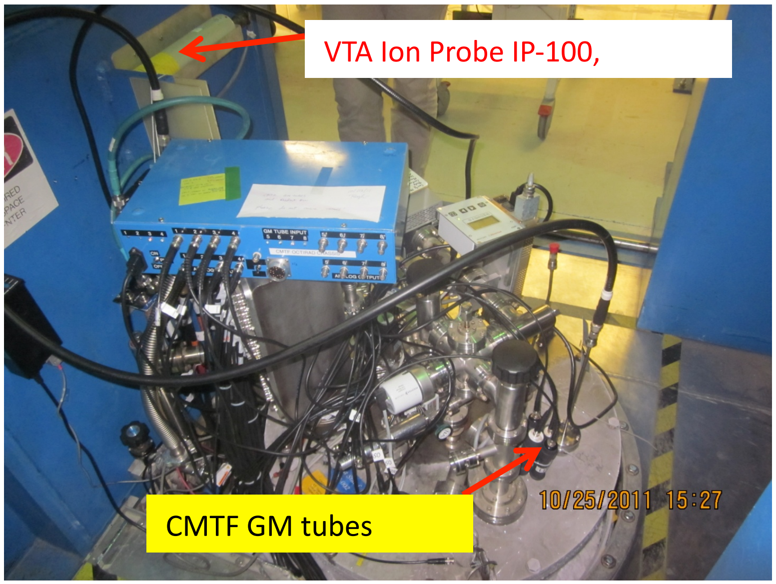
Cavity String/Cryomodue Performance Lessons Learned & Issues of Interest

- Field emission/dark current
  - Situation is improving, still not completely resolved
  - Challenge goes up rapidly with gradient
    - Active subject for ILC 1 TeV cavity gradient R&D
- Q_0 loss
  - CEBAF re-work cryomodule during 2006-2010
    - Final answer yet to be found
- Real estate gradient
  - 7-cell cavity replaces 5-cell cavity during CEBAF upgrade module R&D
- Cryogenic limitation
  - Understanding of critical heat flux in liquid helium tank riser from CEBAF upgrade cryomodule R&D
    - Symptom: LHe boiling >> temperature & liquid helium level instability & microphonics
    - Solution: increase riser pipe diamter >> built into CEBAF 12 GeV project
- Thermal limitation
  - HOM coupler thermal limitation
    - Solution: superconducting niobium probe & sapphire feedthrough
    - Technology used in CEBAF 12 GeV project and European XFEL project
- Vibrations and microphonics

Field Emission Onset in Cryomodule Test
SNS vs. CEBAF 12 GeV Upgrade

	SNS	CEBAF Upgrade
year	2005	2011
	All met or exceeded requirements for gradient or Q0	Test is on-going
Field emission onset Eacc [MV/m] Epk [MV/m]	 5-13 (10 average) 14-35 (27 average) for β=0.61 11-29 (22 average) for β=0.81	 12-22 26-48
Modules tested	9 of 11 β=0.61 2 of 12 β=0.81	3 so far (plan to test all)
Gradient limit VTA Cryomodule	 Field emission during VTA testing Electron loading in cryomodule	 Mostly admin. limit in VTA testing C100-1: All cryo/thermally limit

Cross Checking CMTF GM tubes in VTA

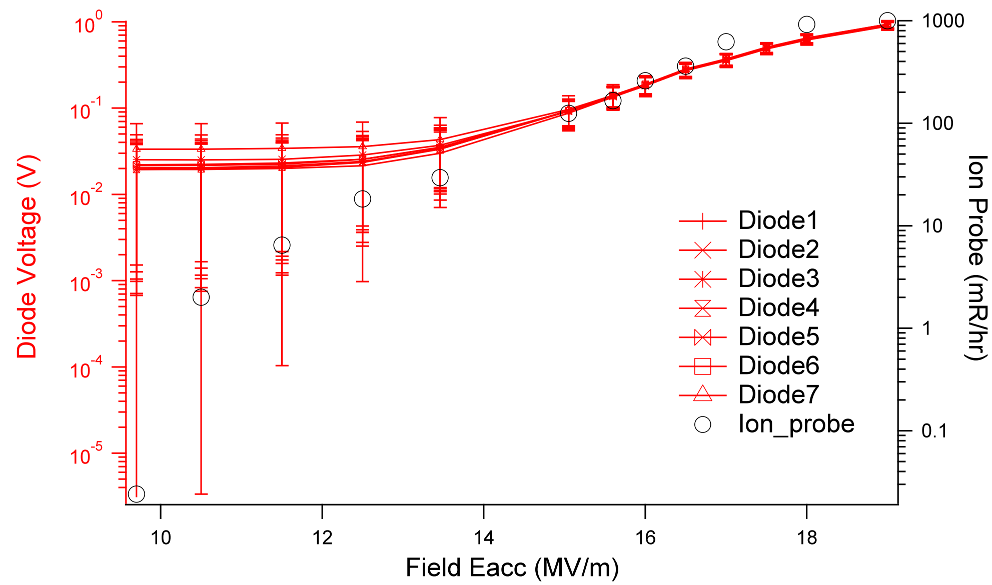


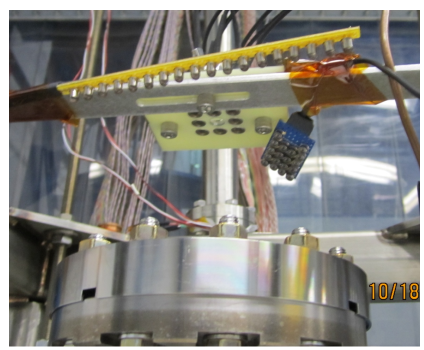
First Results:

Field emission onset predicted by CMTF GM tubes is delayed by 3-6 MV/m compared to that by VTA ion probe

Development of cryogenic radiation detector for "at-cavity" radiation measurement

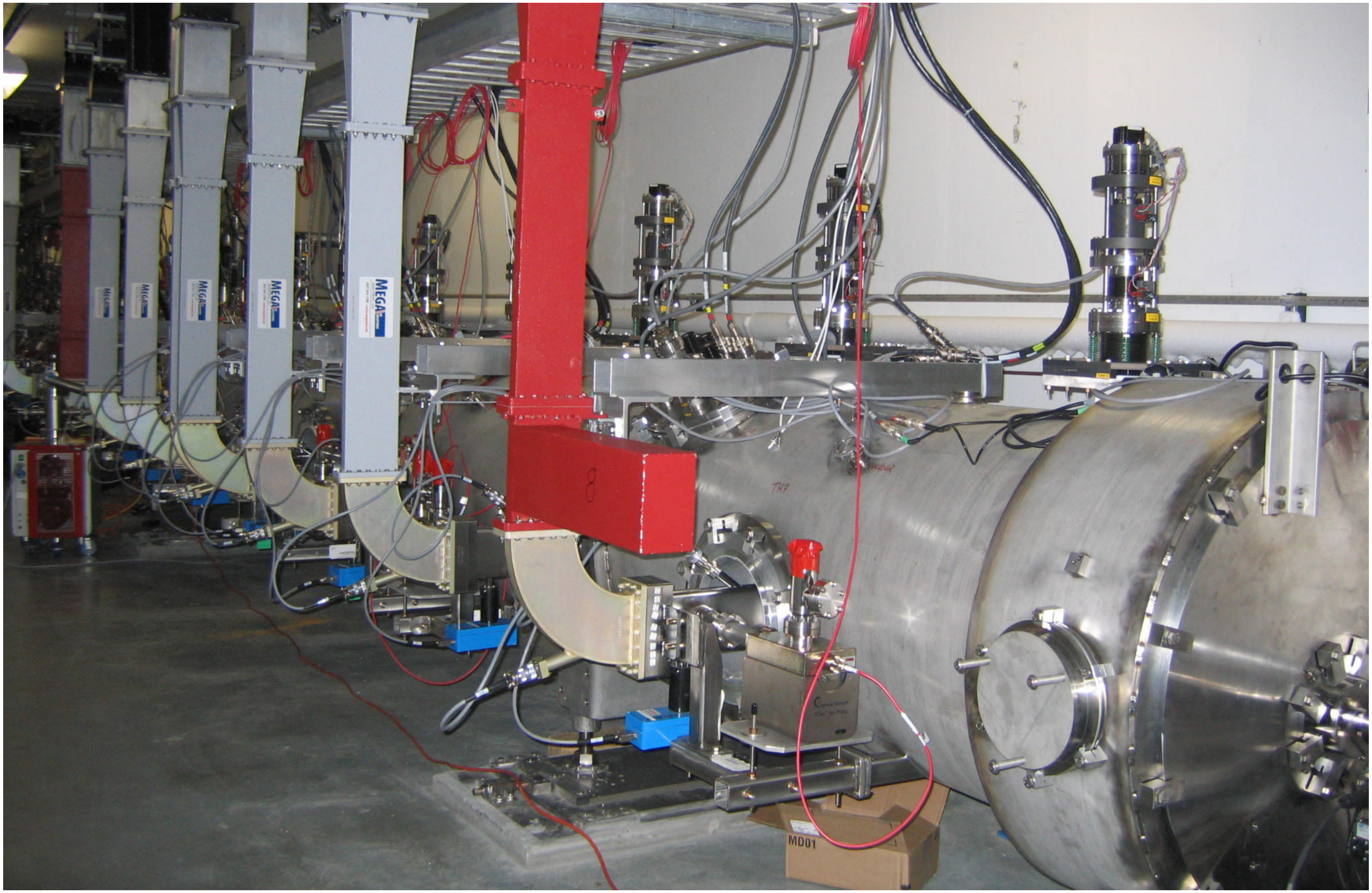
Work supported by ILC Cavity Gradient R&D and applicable to CEBAF





8 – Hamamatsu S1223 Diodes (provided by KEK STF) mounted above 9-cell cavity RI23

C100 Cryomodule in CEBAF tunnel



Current Status of Cavity String & Cryomodule for CEBAF 12 GeV Upgrade

- 86/86 (100%) cavities received from vendor
- 86/86 (100%) cavities completed EP processing
- 67/86 (78%) cavity vertical test completed
- 7 (70%) hermetic cavity strings completed
  - On track to deliver all 10 cavity string by Feb 2012
- 3 cryomodules under testing
  - C100-1 & C100-2 in CEBAF tunnel
  - C100-3 in Test Lab CMTF

New SRF Infrastructure at JLab for Future SRF Technology and Projects

Conclusion

- JLab has accumulated cavity string/cryomodule experience with ~ 80 cryomodules and ~ 500 multi-cell cavities for CW electron and pulsed proton acceleration.
  - JLab delivered an integrated cryomodule field of 820 MV which was used for acceleration of proton beam up to 26 mA at SNS.
  - We have had an integrated cryomodule field up to 1200 MV and an accelerated current up to 900 μA electron beam at CEBAF, but not simultaneously.
- Many issues of interest have been identified and understood and solutions built into cryomodules for new projects.
- We are continuing to optimize the operating parameters of CEBAF cryomodules.