20 Years' Experience with the World's Largest Superconducting RF Application: CEBAF

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Outline

- CEBAF – the Continuous Electron Beam Accelerator Facility
- Superconducting RF technology, SRF – what is it?
- SRF circa 1992 @ CEBAF construction
- Enables Continuous beam – precision control, high data rates
  - Low energy spread - $\Delta E/E \sim 6 \times 10^{-5}$ FWHM
- Evolution of SRF technology folded back into improved CEBAF
  - Cleanliness >> reduce field emission >> higher energies
  - Refined surfaces >> increased *Q* >> lower cryo requirements >> less $
  - 4 GeV >> 5.5 GeV >> 6 GeV >> 12 GeV
- Improving original cryomodules
  - *In situ* improvements and "C50 program"
- New generation of cryomodules for 12 GeV Upgrade
  - State-of-the-art performance
- Future opportunities
  - Energy efficiency
  - Lowering costs

CEBAF

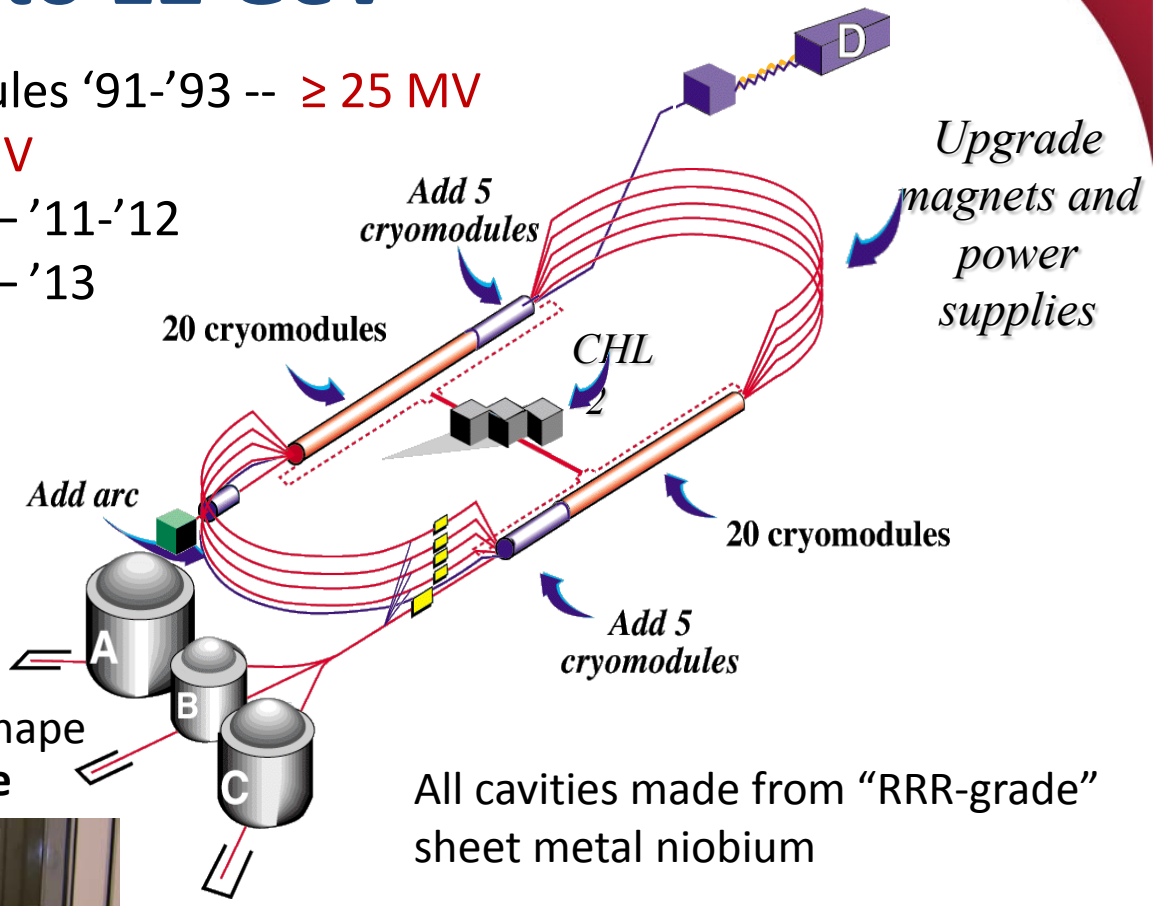
- The CEBAF SRF electron accelerator at Jefferson Lab has completed 18 years of physics research operation
- Three independent 599 MHz polarized electron bunch streams
  - Supporting >175 major nuclear physics experiments
  - >420 PhD's in NP, >200 more in progress
  - 289 Physics Letters and Physical Review Letters publications
  - >925 publications in other refereed journals

- CEBAF has far exceeded its original performance requirements and via its current 12 GeV Upgrade Project is poised for breakthrough research in the coming decades.

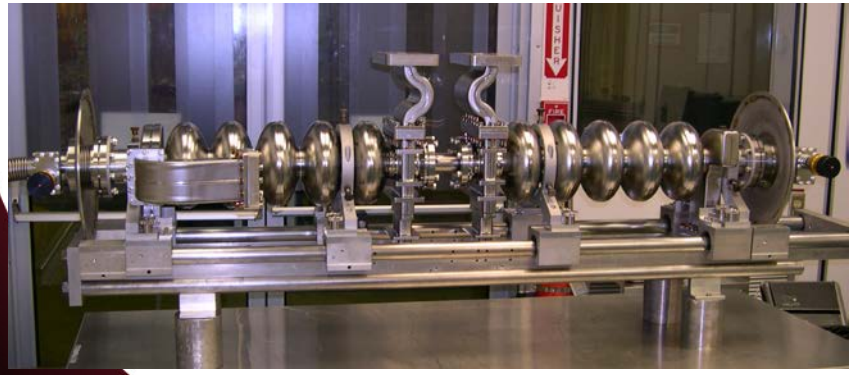
- **Its cw operation and precision beam characteristics are made possible by exploitation of superconducting rf (SRF) accelerating structures.**

CEBAF's Evolution to 12 GeV

42 1st -generation SRF cryomodules '91-'93 -- ≥ 25 MV
10 reprocessed '06-'09 -- 50 MV
4 2nd-generation cryomodules – '11-'12
6 2nd-generation cryomodules – '13
≥ 108 MV avg.
300 W @ 2.07K



Pair of 0.5 m cavities:, "Original" cell shape 1.497 GHz, **8 cavities/cryomodule**



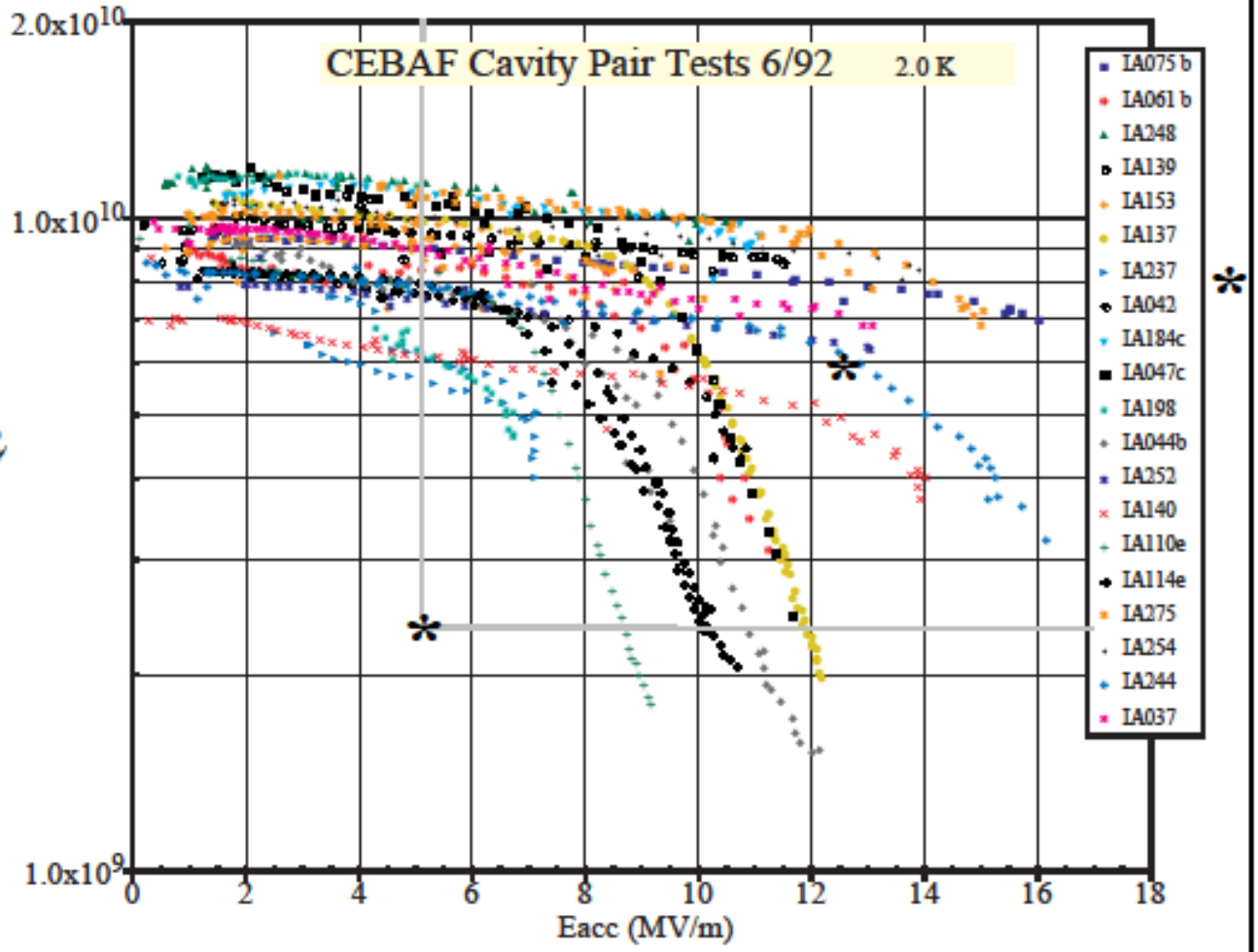
All cavities made from "RRR-grade" sheet metal niobium

2nd generation cavity: 0.7 m, "Low loss" cell shape, 1.497 GHz, **8 cavities/cryomodule**

CEBAF Cavities

State of the Art - 1992

One month's worth of production cavity testing for CEBAF in 1992.



Jefferson Lab

Thomas Jefferson National Accelerator Facility

SRF Talk 17 Oct 2001

Operated by the Southeastern Universities Research Association for the U.S. Depart. Of Energy cer

CEBAF Operation

Original 1986 design:

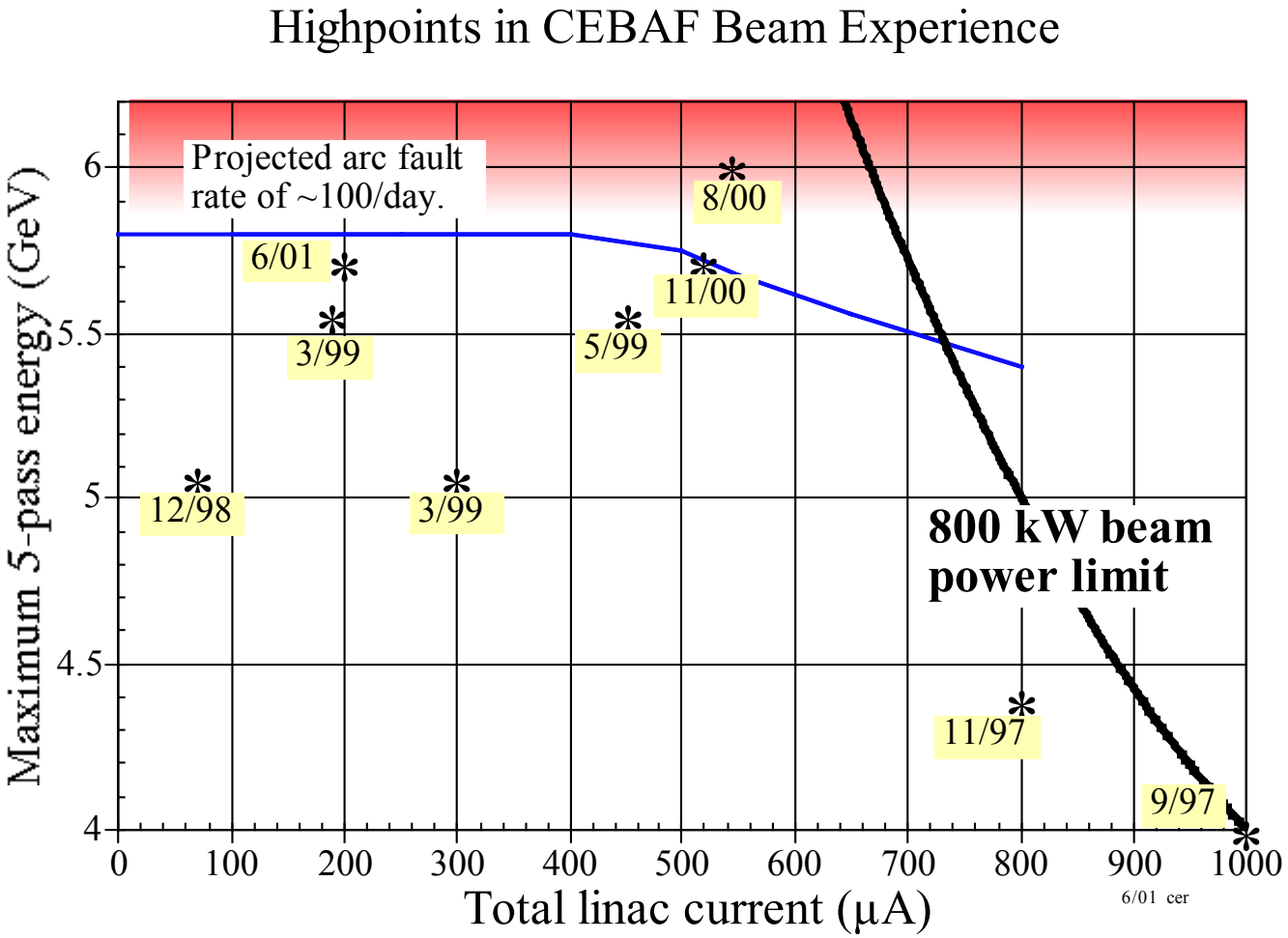
4 GeV with 200 μA,
five-pass beam

Routine in 2001:

5.7 GeV with 100 μA,
five-pass beam,
>75% polarization

Routine in 2012:

6.0 GeV with 150 μA,
>85% polarization,
energy spread
FWHM < 6e-5

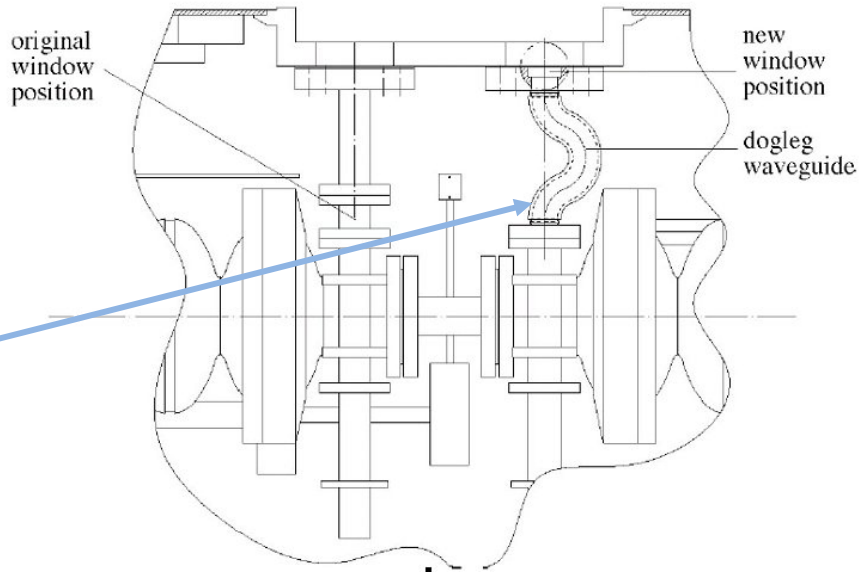


354 individually controlled 1497 MHz SRF cavities in 44.25 cryomodules

Rework of CEBAF Cryomodules – C50 program 2006-2009

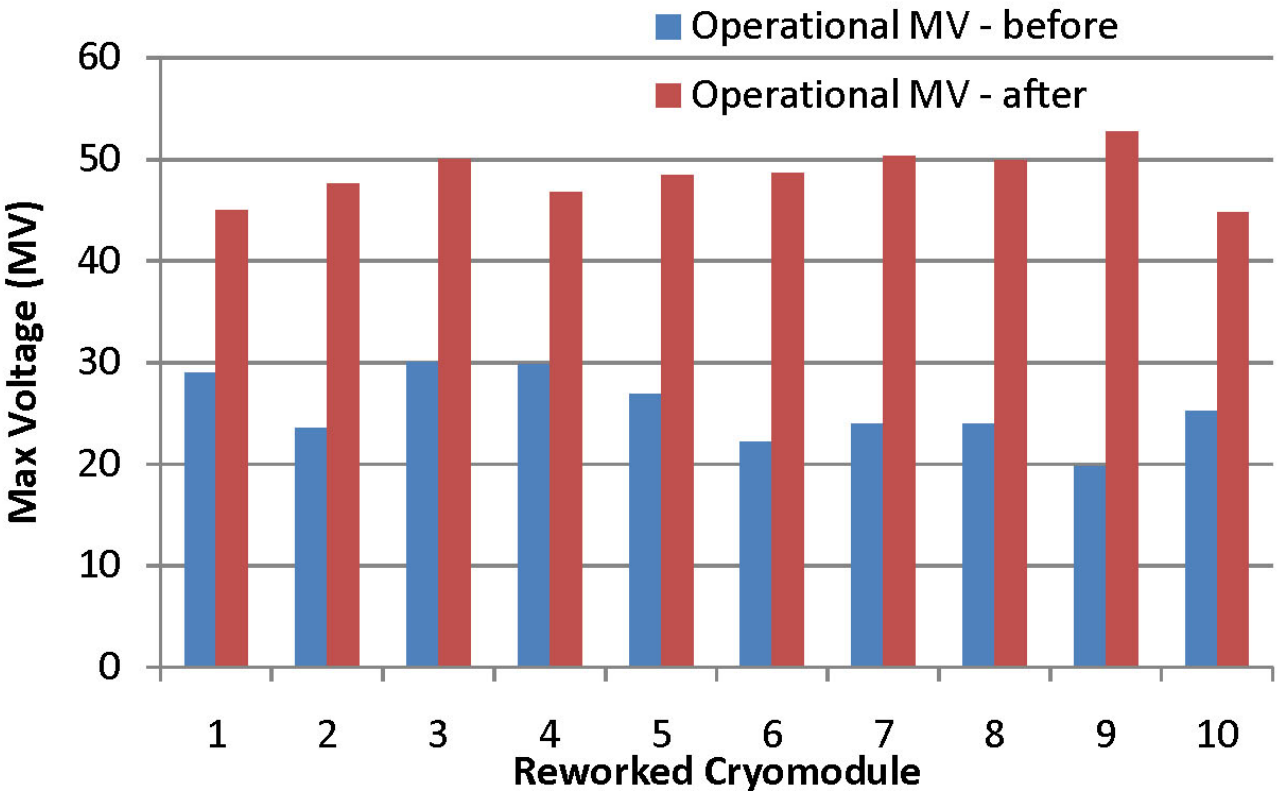
- **Objectives**
  - **Clean-up field emission which produces heat and window arc trips**
  - **Raise useful gradients from ~5.5 MV/m to 12.5 MV/m**

- Ten cryomodules were fully disassembled
- Cavities (fabricated 1991)
  - Baked @ 600°C, hydrogen degas
  - Tuned
  - 30 μm BCP etched surface
  - High pressure ultra-pure water rinse
- Cold rf window moved outboard of new "dogleg" waveguide section
- Cavity pairs assembled under improved cleanroom conditions
- Cryomodules were reassembled, tested, and reinstalled in CEBAF



M. Drury, et al., "Summary Report for the C50 Cryomodule Project"
http://accelconf.web.cern.ch/AccelConf/PAC2011/papers/tup108.pdf

Rework of CEBAF Cryomodules – C50 program 2006-2009

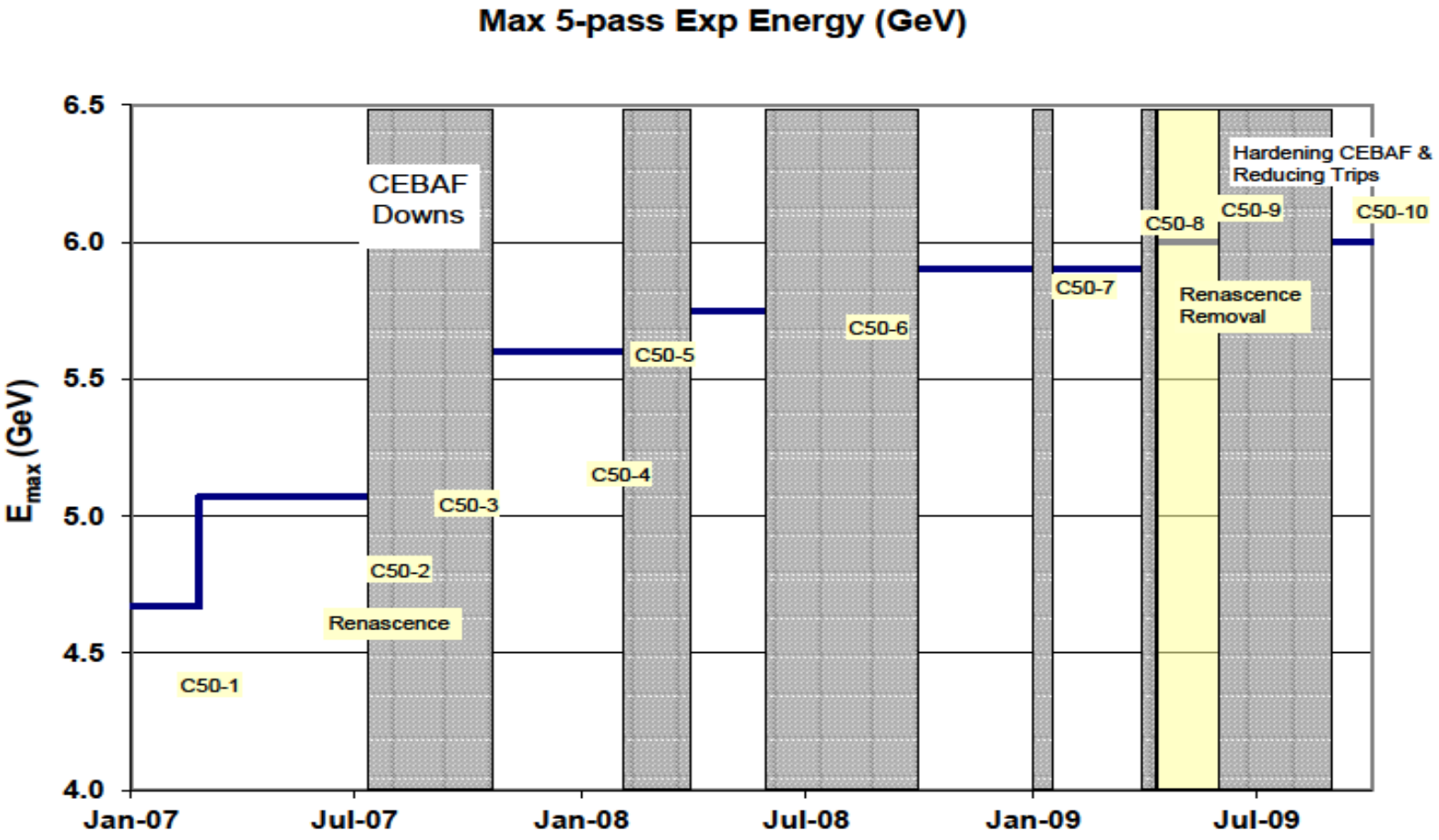


Operating range in CEBAF is limited to 13.5 MV/m by RF power

- **Excellent improvement in gradient**, field emission effects effectively eliminated
- *Q*'s still low in cryomodule – now attributed to nearby **unrecognized magnetized components**

Rework of CEBAF Cryomodules – C50 program

- Established a solid 6 GeV base for the 12 GeV upgrade, cryo heat load is higher than desired
- Operational setup now considers cavity 2K W/MV as well as MV/m in gradient distribution algorithm

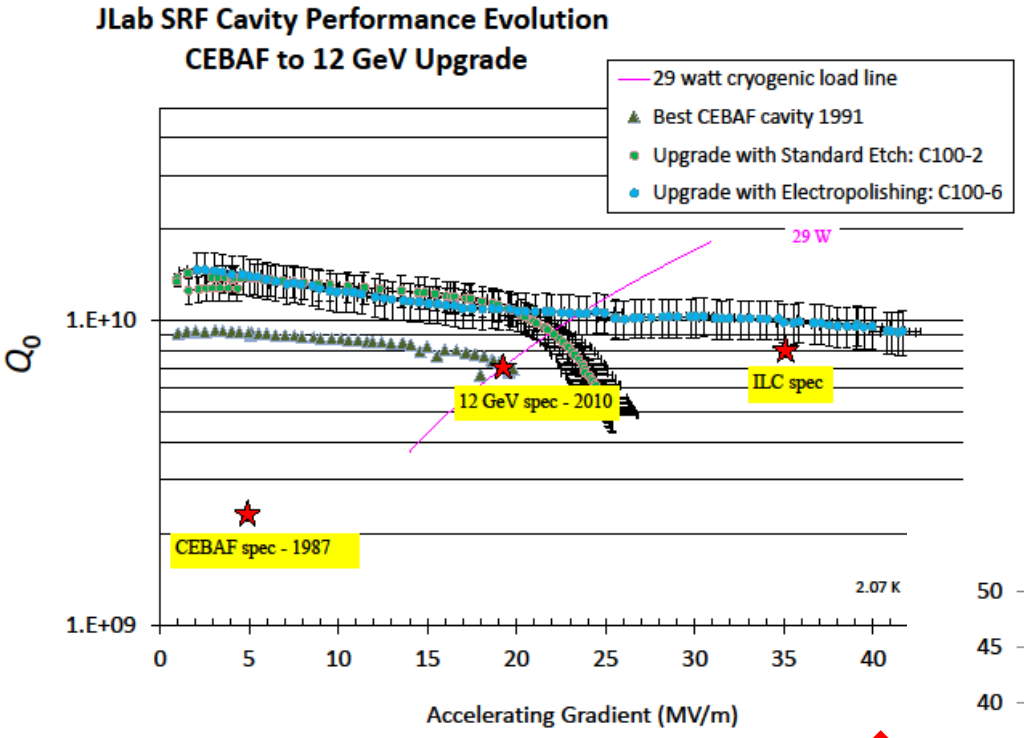


Evolution of CEBAF energy with C50 progress

CEBAF is evolving with SRF Technology

What is the real growing-edge experience with bulk niobium SRF systems for operational electron linacs?

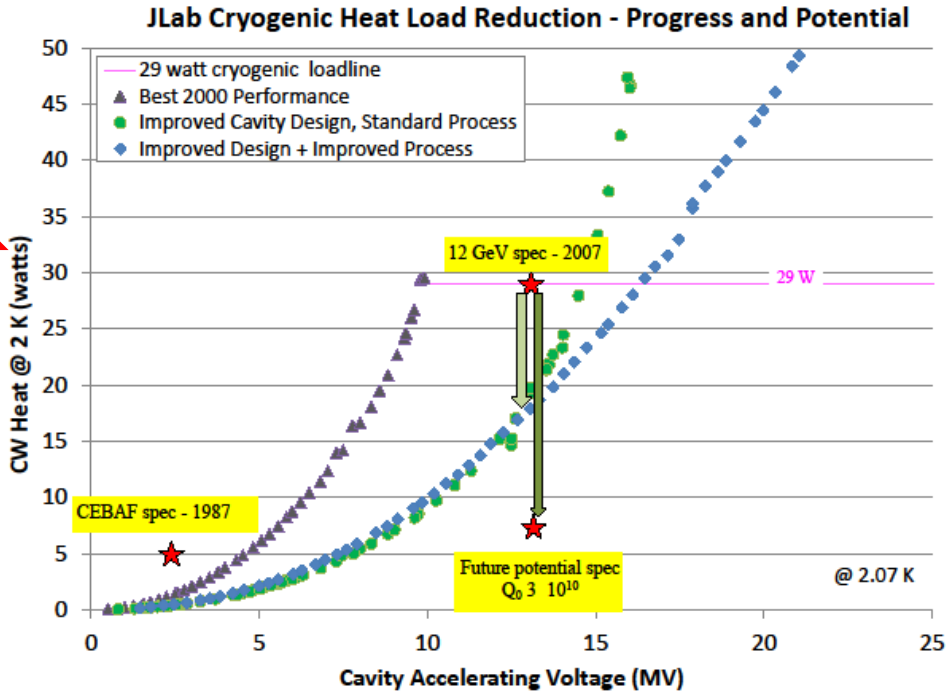
- **Contamination control** → field emission and heat
- **Magnetic field environment** → heat → cryo costs
- **Cavity processing protocol** → reliable optimum results
- **Fabrication tolerances** → confident beam stability
- **Heat management** → operational limitations & cost
- **Seals and gaskets** → vacuum leaks
- **Microphonics management** → rf power efficiency



The key figures of merit are ***Q*** and **Accelerating Gradient.**
Together with structure geometry, these determine the **heat produced.**

same data

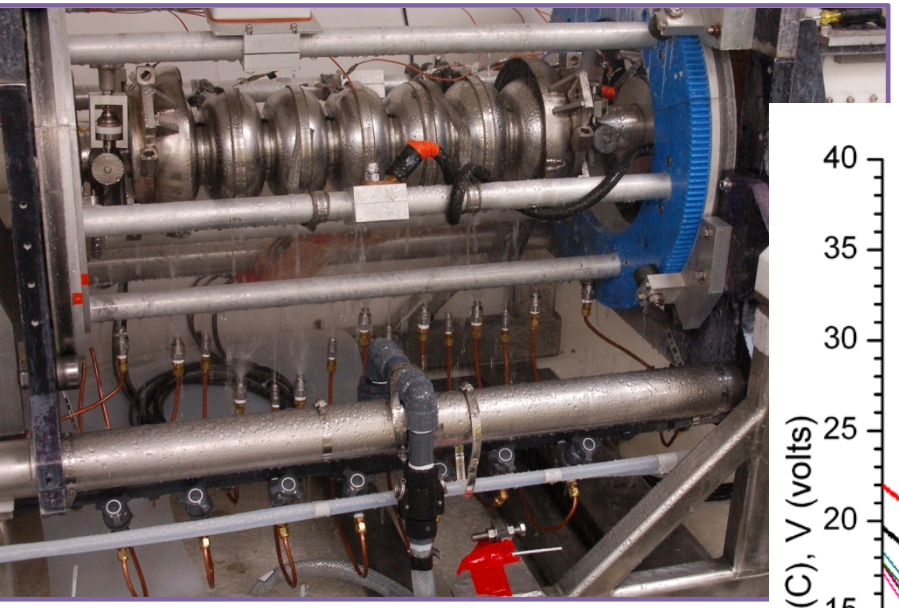
higher cryo costs

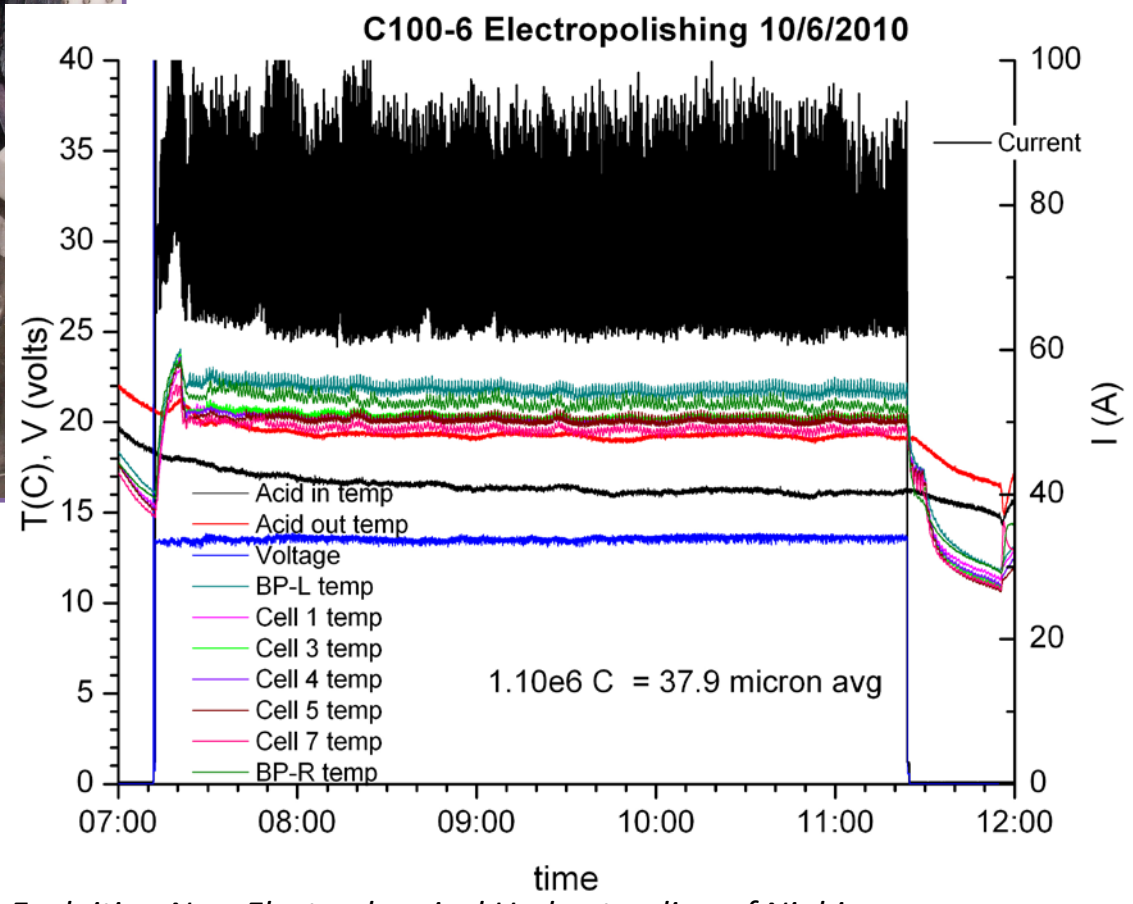


more compact accelerator

12 GeV Upgrade Cavities

- Improved electropolishing process is now standardized and controlled

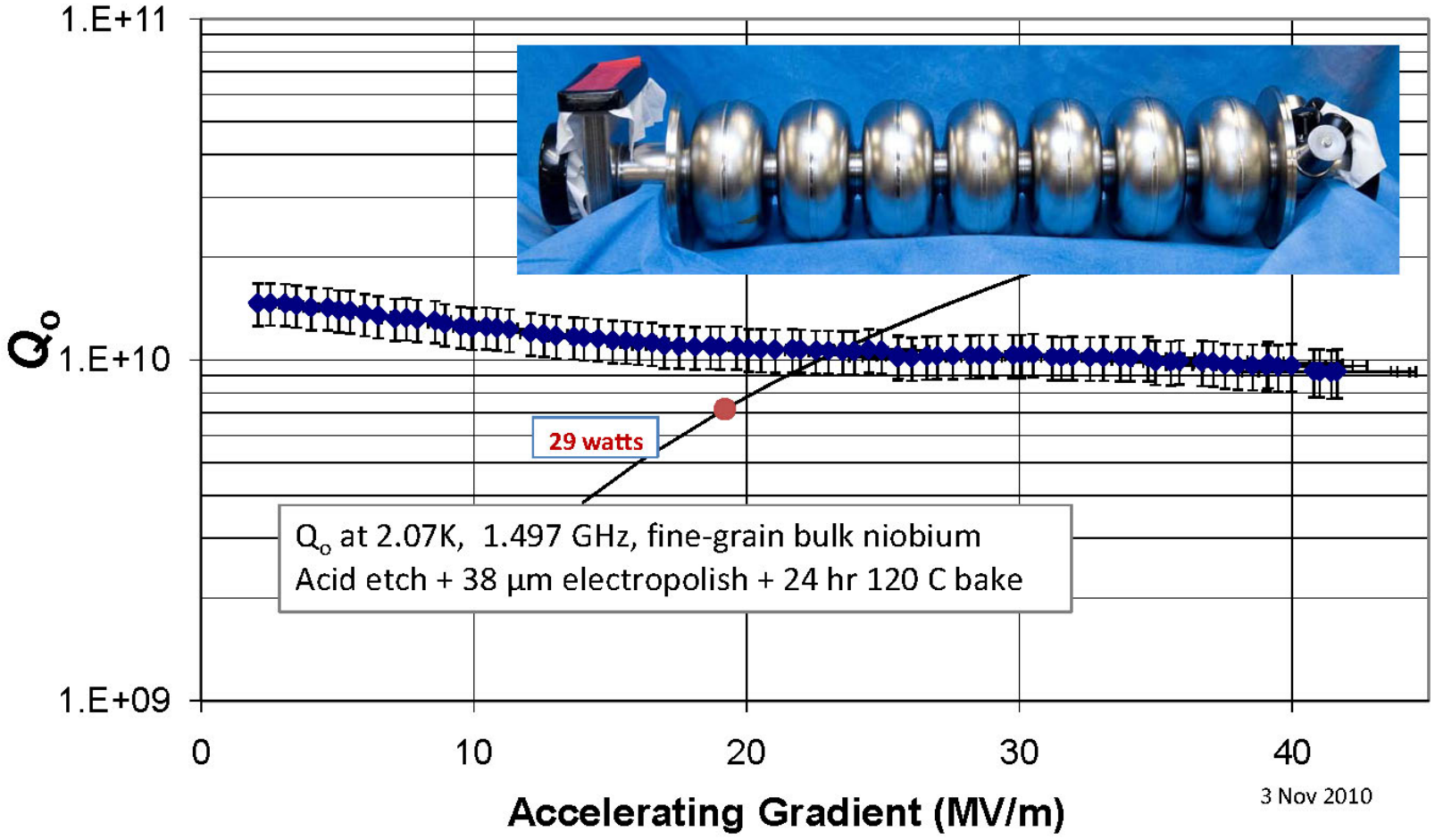




C. E. Reece and H. Tian, *Exploiting New Electrochemical Understanding of Niobium Electropolishing for Improved Performance of SRF Cavities for CEBAF*
THP010, LINAC10

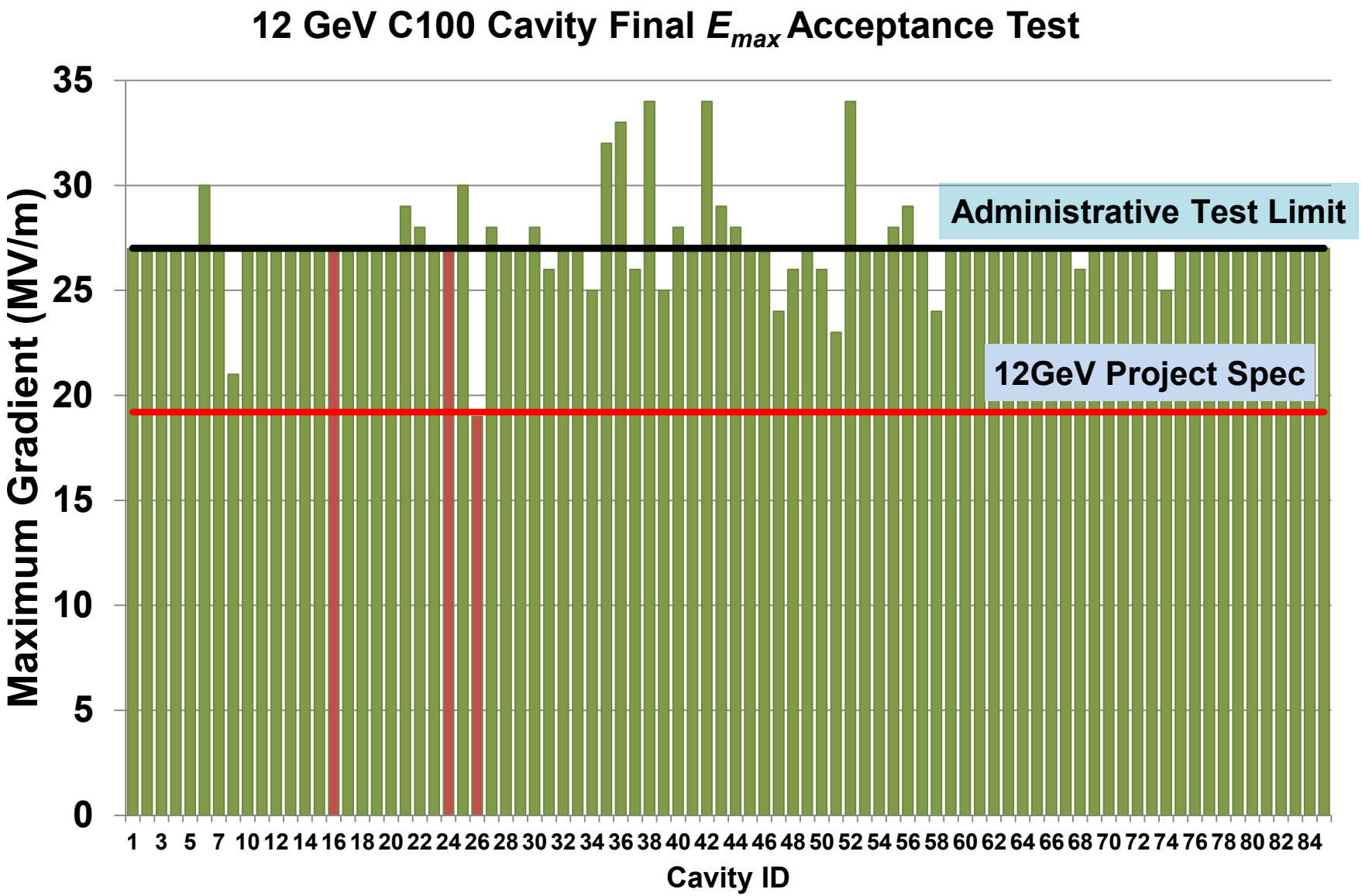
State-of-the-art production SRF cavity

C100-6



(*Q* is BCS-limited)

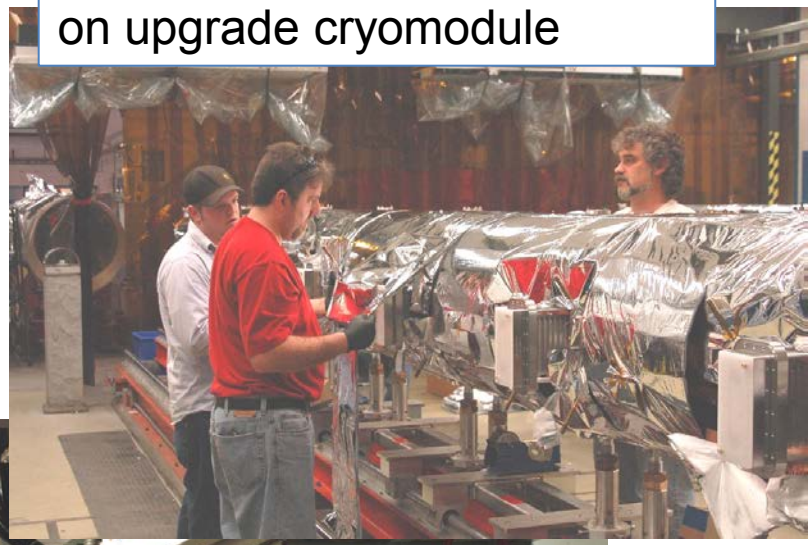
CEBAF 12 GeV project cavities



12 GeV Upgrade Cryomodule

First cavity string @ completion

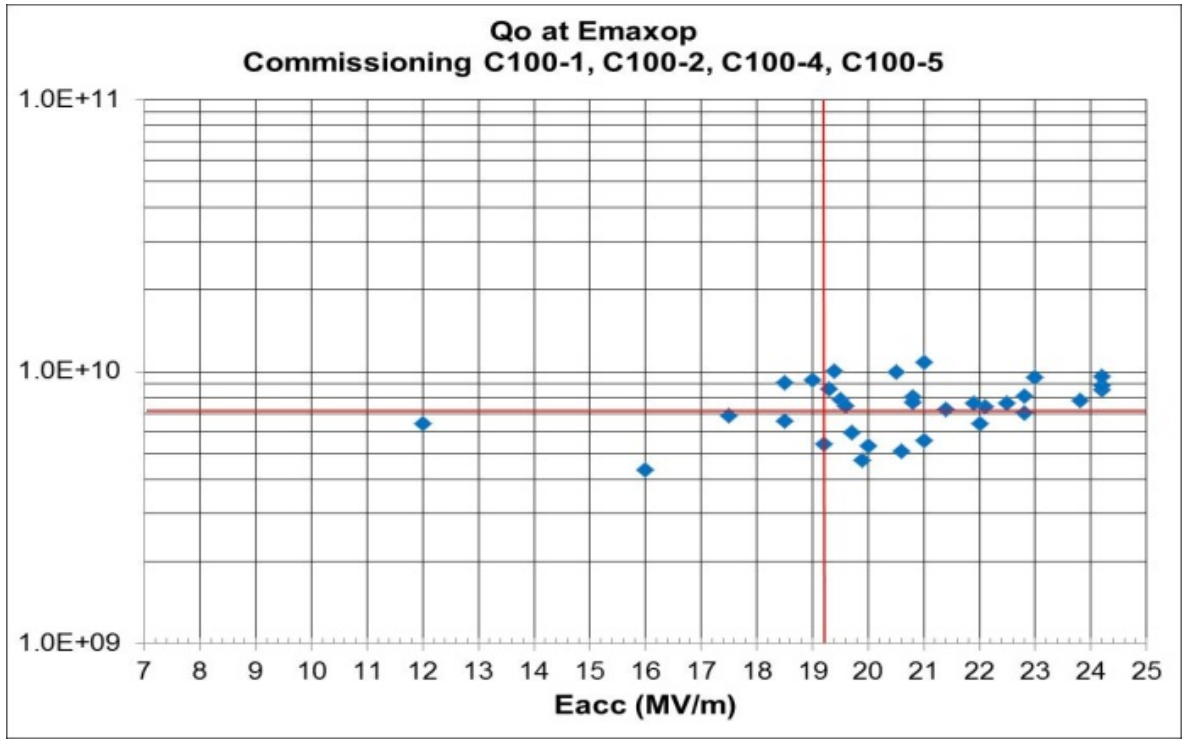
Installation of super-insulation on upgrade cryomodule



Two new cryomodules staged for installation in CEBAF tunnel

12 GeV Upgrade Cryomodule Performance – Sept. 2012

- **First four cryomodules commissioned**



2.07 K

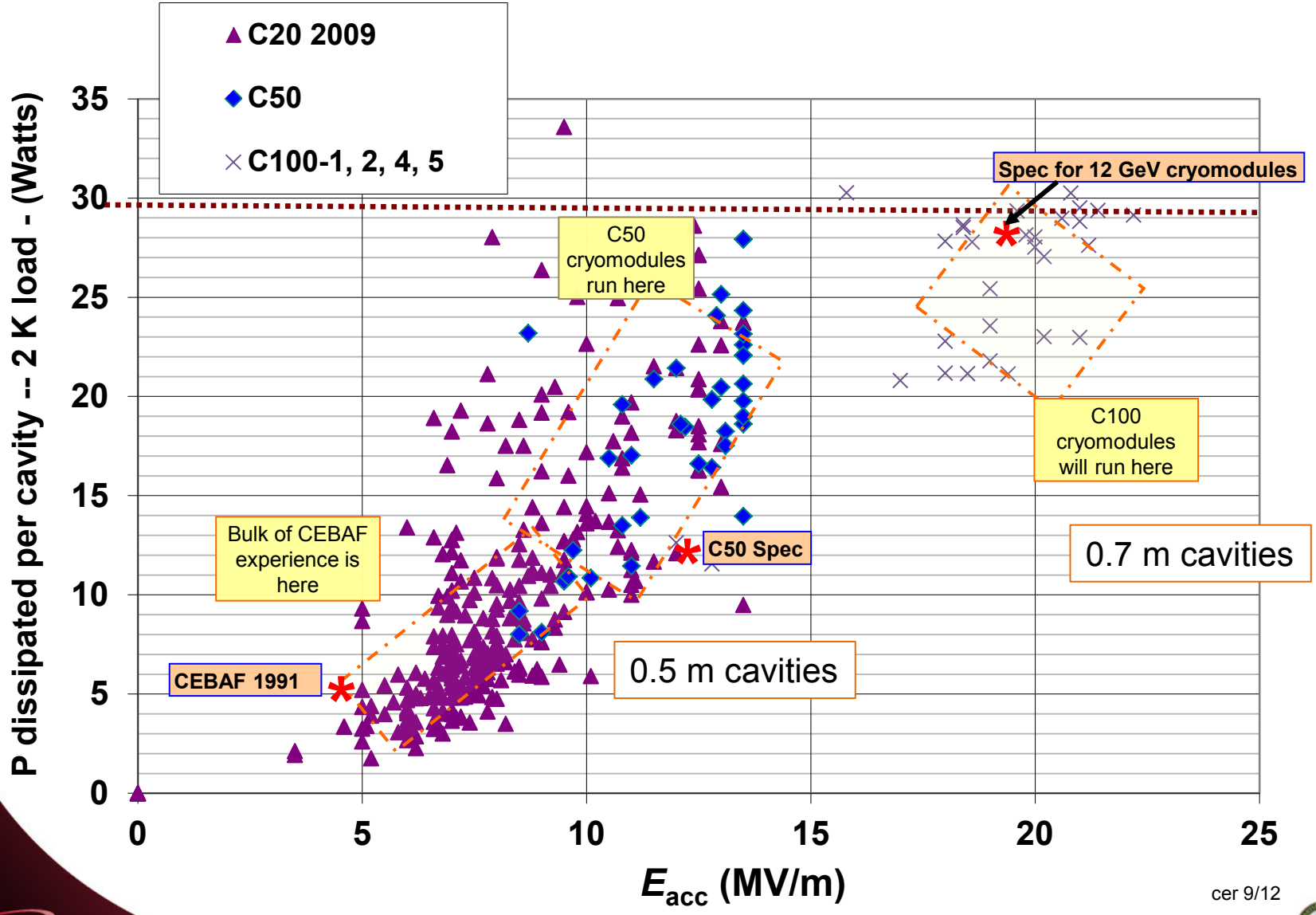
On May 18, 2012, C100-2 was operated at 108 MV for over an hour at 465 μA, the design current for 12 GeV CEBAF.

- M. Drury *et al*. LINAC12 MOBP030

Cryomodule Energy Gain (MeV)

	Acceptance	Commission	Ops
C100-1	111.7	104.3	94.5
C100-2	117.5	109.6	108
C100-3	118.7		
C100-4	115.1	105.8	106.2
C100-5	108.2	109.9	109.3

2 K Dynamic Heat Load vs. Cavity Gradients in CEBAF



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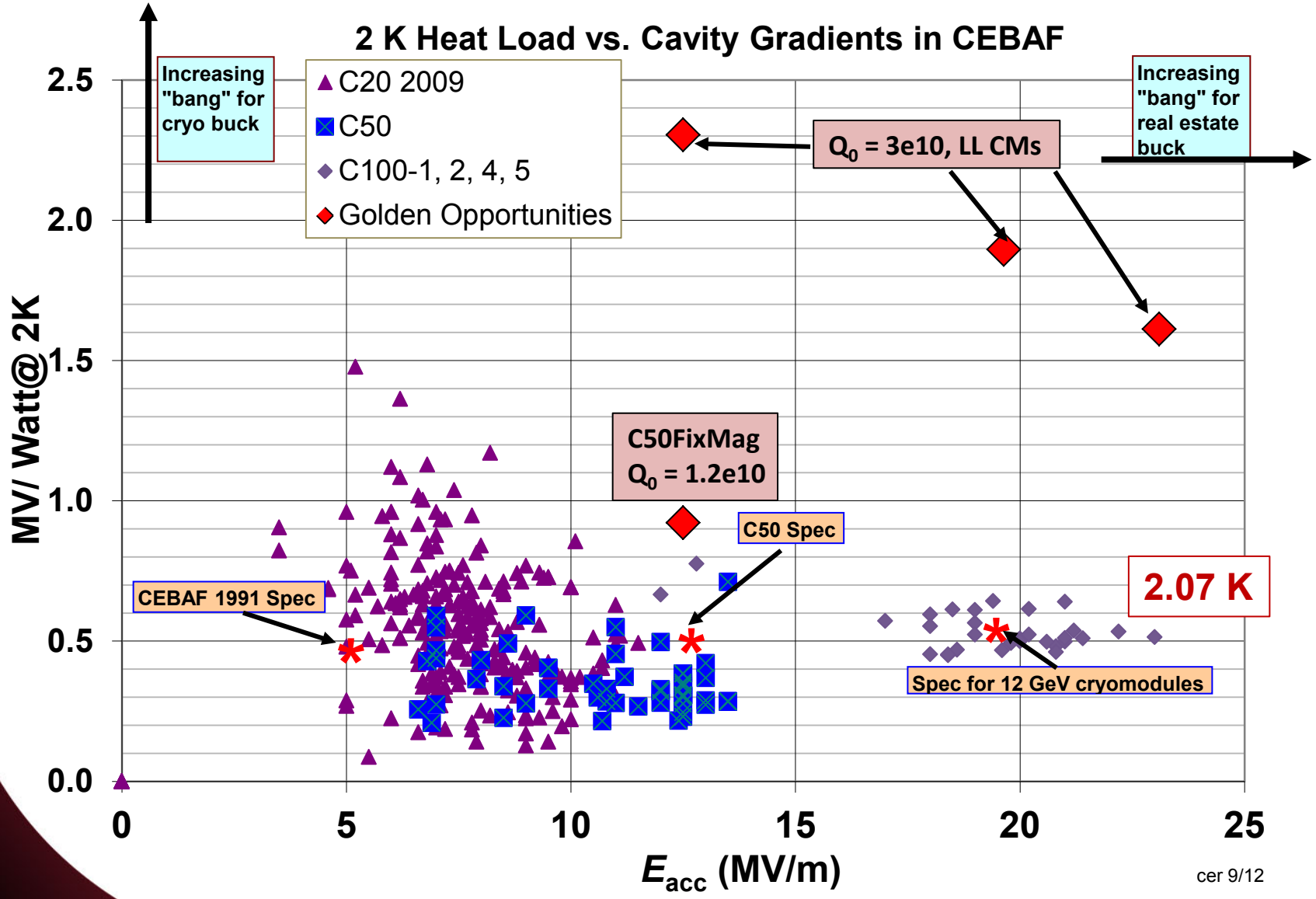
Bang for the Cryo Buck



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Jefferson Lab Technology and Engineering Development Facility Project (TEDF)

A DOE Science Laboratory Infrastructure modernization project

Provides the first 2nd-generation SRF facility in the world

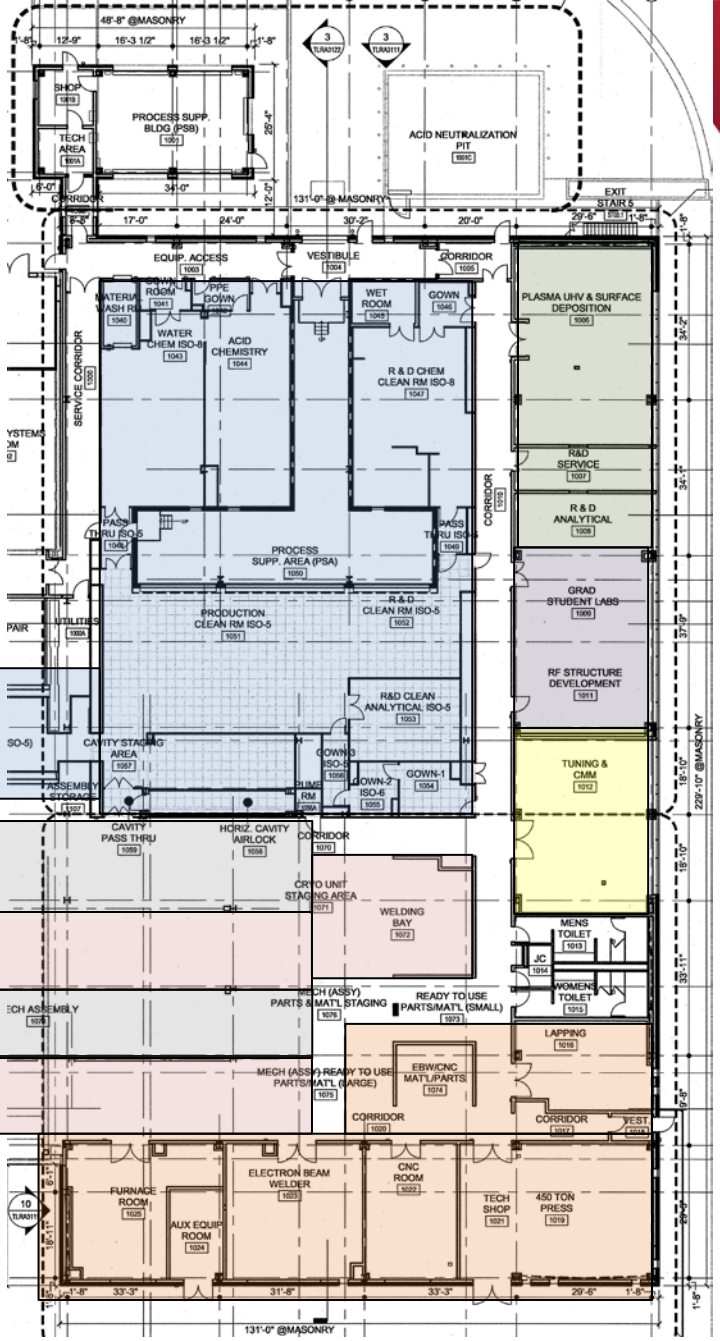
Completion: 2013

October 2011

TEDF SRF Infrastructure Design

30,000 sf – all new

- RF structure development
- Cavity fabrication (presses, EBW…)
- QC/ Inspection
- **Integrated cleanroom suite**
  - Production chemroom
  - R&D chemroom
  - Flexible ISO 4 assembly areas
  - Clean material analysis lab
- New materials R&D lab
- Dedicated CEBAF-support CM assembly lines
- Expansion assembly space for other DOE project support



Next SRF Advances …

- **Exploit new insights from material science research**
  - Efficient and confident surface prep – manage topography & surface chemistry for minimum R_s
  - Green and efficient processing methods – reduce or eliminate use of HF
  - New materials to lower cryogenic power requirements – Nb_3Sn ?
  - Reduce costs via thin film superconducting materials – Nb on Cu

- **Advanced structure designs for specialized applications**
  - Crabbing for maximum EIC luminosity
  - Spin-offs to next-generation terahertz-to-x-ray light sources and high-current proton applications for neutron sources

Evolution of CEBAF via SRF R&D

Conclusion

- SRF technology at JLab continues to develop, 25 years and counting.
  - 5 MV/m ⇒ 40 MV/m
  - Improved cavity Q_0 by factor of 4
    - Another factor of 2-3 may be on the horizon for major system cost reduction

- Benefiting from this progress, CEBAF remains the US flagship of SRF-based accelerators and is poised to remain a premier NP research tool in the coming decades.

- While primary attention gets focused on SRF cavity performance, economical system integration solutions remain a challenge and opportunity.