SRF Science and Technology

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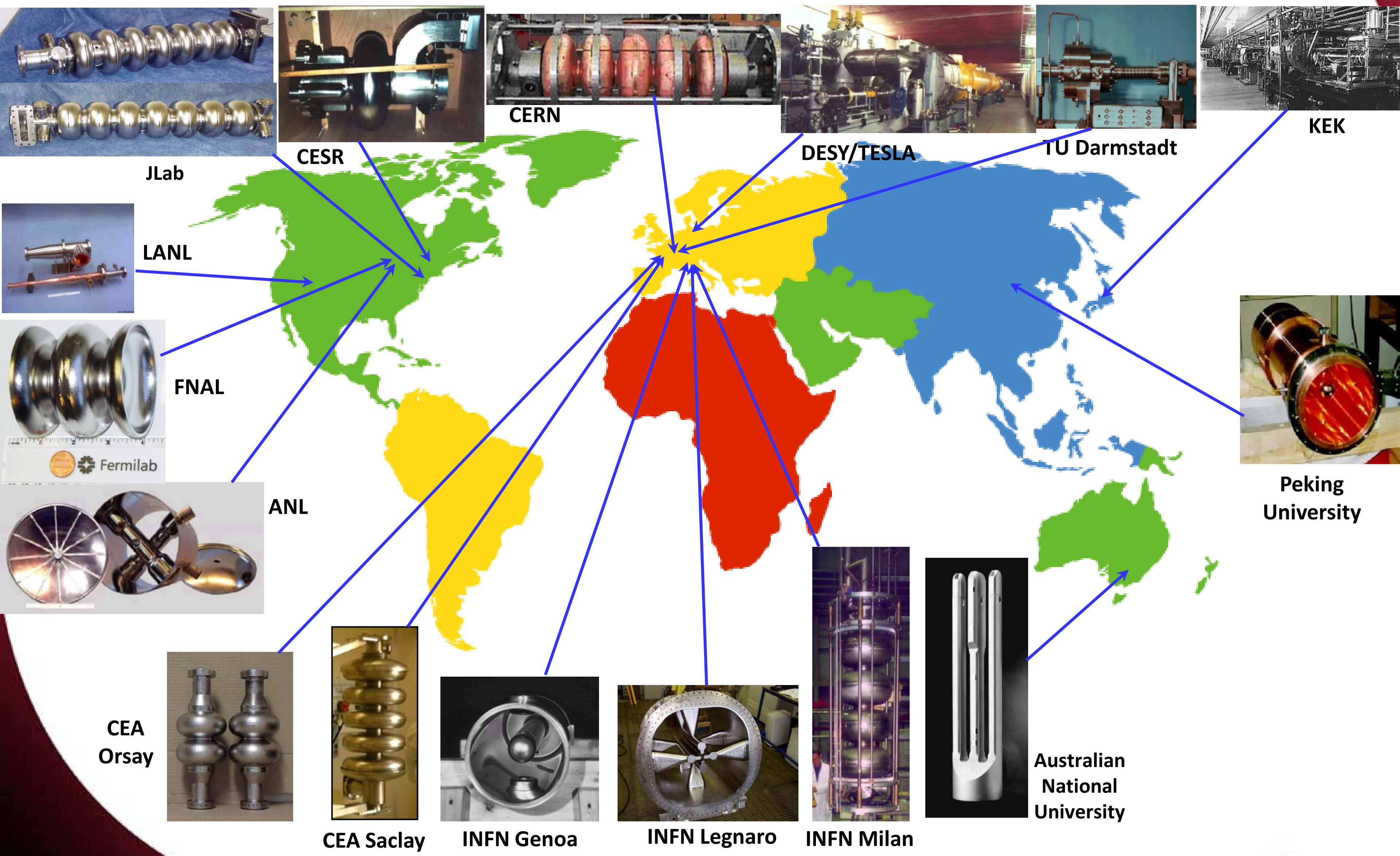
What is SRF?

SRF is the exploitation of superconducting properties of particular materials to provide energy efficient, high performance accelerator systems.

- Superconducting radio frequency (SRF) technology is a multi-disciplinary field requiring significant system integration.
- The principal virtues of this technology applied to particle accelerators are
  - CW (non-pulsed) operation with **efficient conversion** of rf power into beam power
  - Large beam apertures, which enable **precision control** of beam optics (low emittance)
- Essentially all new large accelerators being planned in the world aim to exploit this technology.
- CEBAF was the first large-scale application of SRF in the US – constructed 1987-1993.

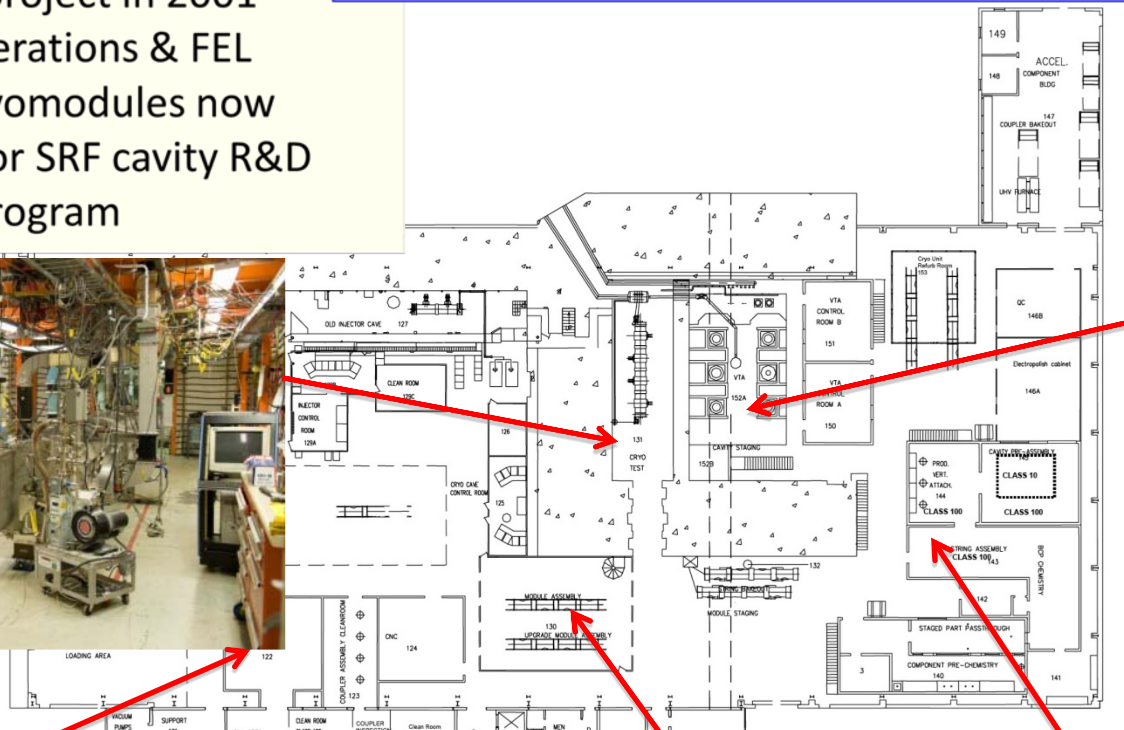
SRF – A Robust Global Technology

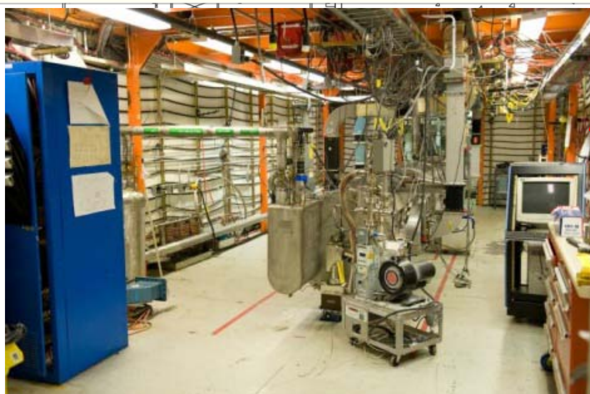


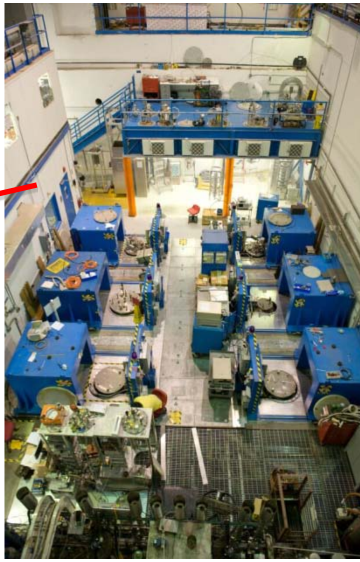
JLab Institute for Superconducting RF Science and Technology

- Established for CEBAF construction
- Upgraded for SNS project in 2001
- Supports 6 GeV operations & FEL
- Building 12 GeV cryomodules now
- Leading US effort for SRF cavity R&D
- Active education program

Only place in the world with concept-to-delivery SRF capability



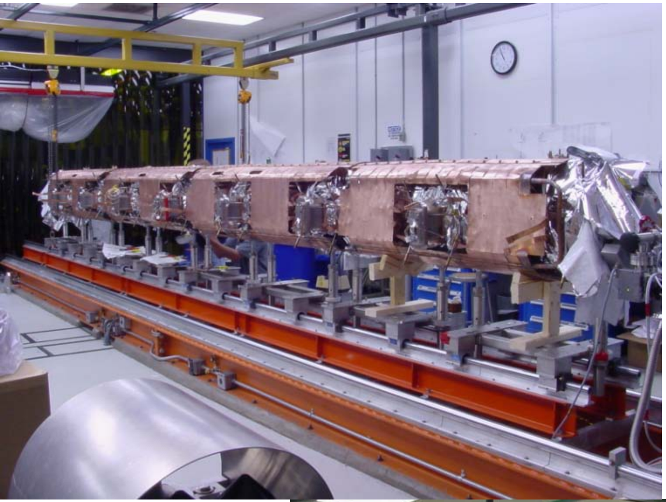


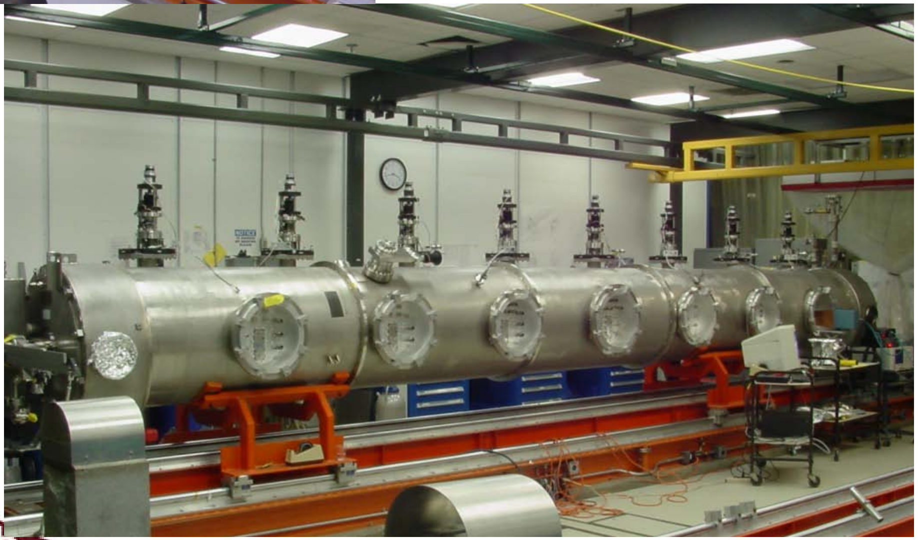


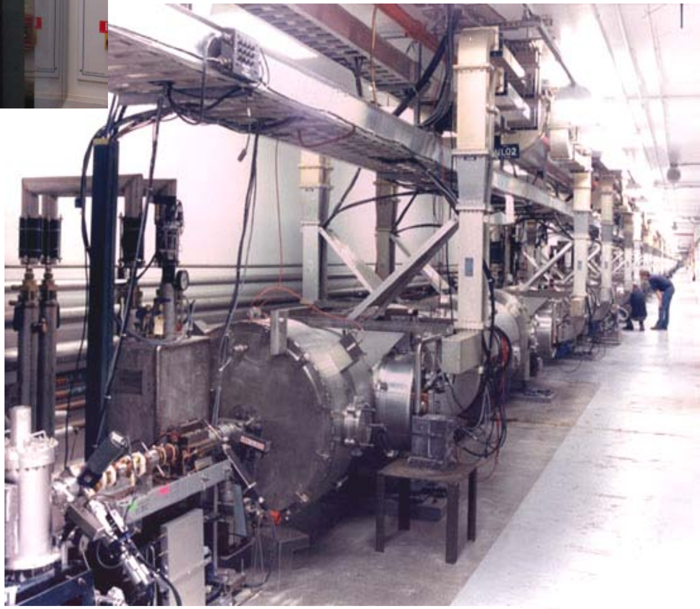
JLab SRF Experience

- The SRF Institute has fabricated and/or processed a wider variety of multi-cell SRF cavities than anyone else
  - 96 cavities fabricated / >720 multi-cell cavities processed
  - 26 different cavity types processed
- In addition, a large number of smaller test cavities have been fabricated and/or processed for materials and processes R&D
- >3400 individual cryogenic cavity tests since 1991
- Assembled and delivered 84 completed cryomodules
  - 43 for CEBAF
  - 4 for JLab FEL
  - 23 for SNS @ ORNL
  - 2 for others
  - Refurbished 10 cryomodules for CEBAF
  - 2 for 12 GeV CEBAF

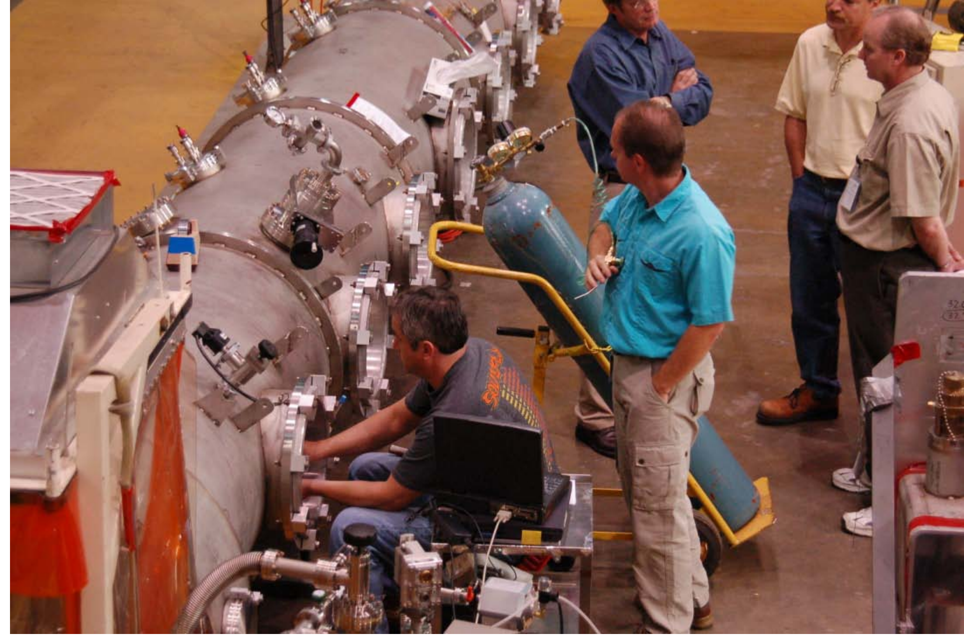
SRF Photo gallery





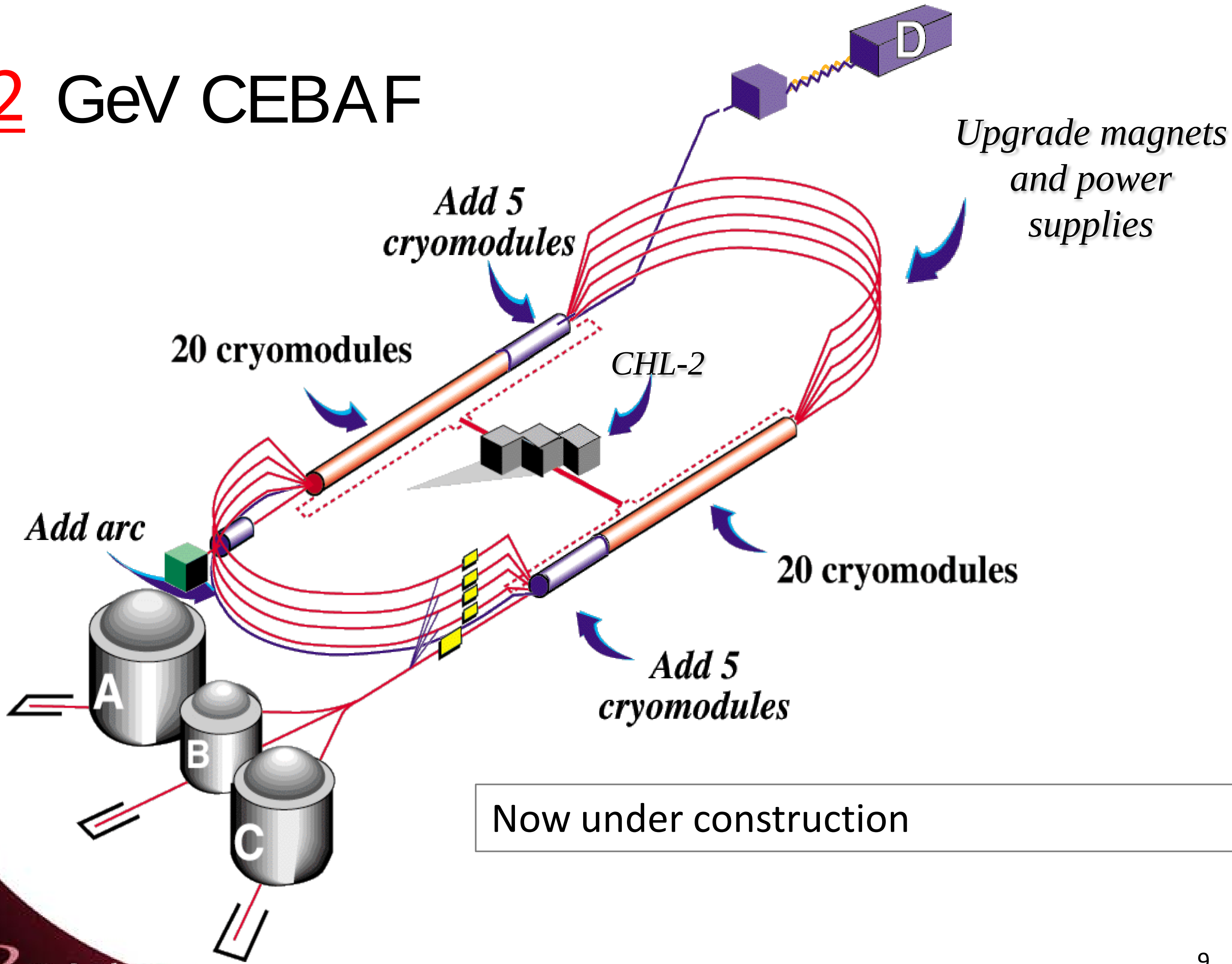


SRF Photo gallery

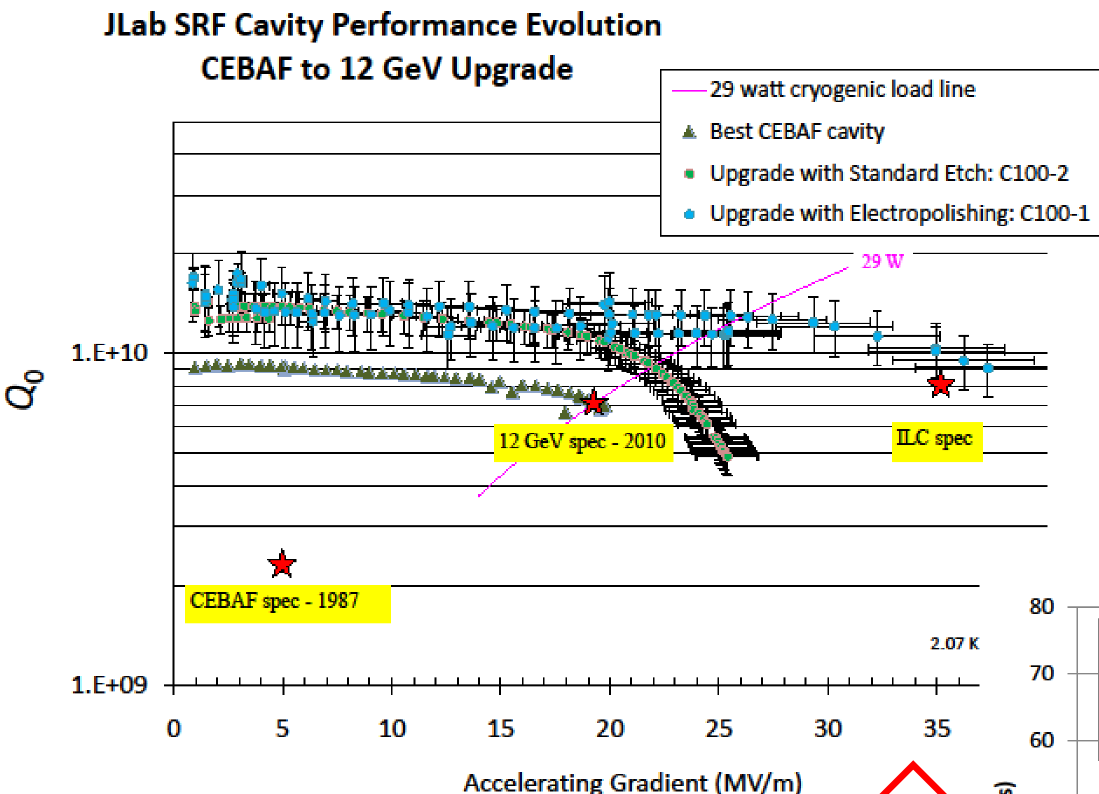


CEBAF 12 GeV Upgrade

12 GeV CEBAF



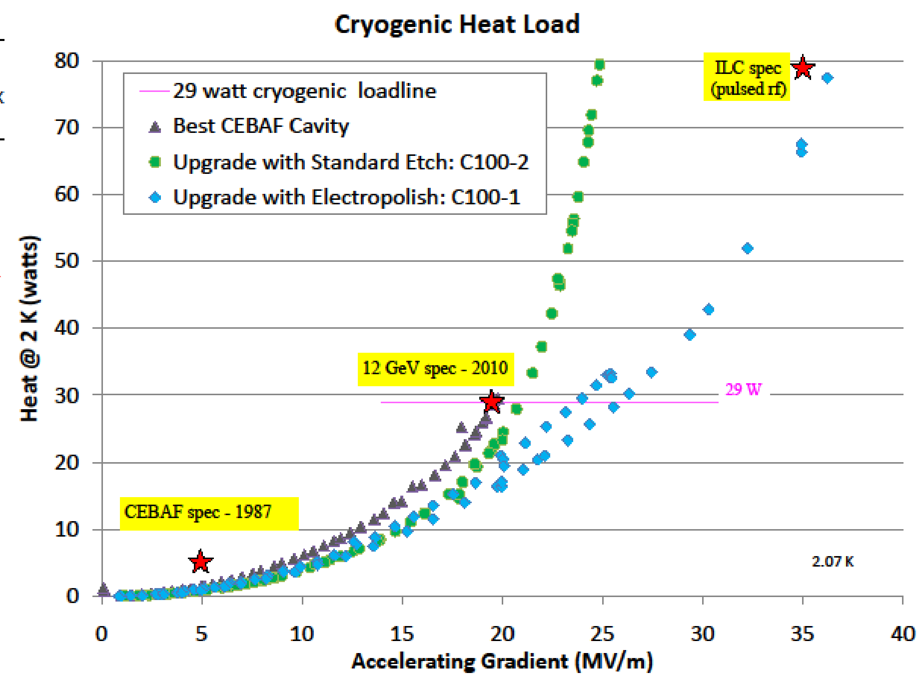
Now under construction



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

SRF Institute

- A large part of our mission is to **develop new design solutions** for applications at JLab and other DOE facilities – and also collaborate with international partners.
  - These design solutions typically push the state-of-the-practice envelope.
- Another part of our mission is **research on materials and processes** that pave the way to new future capabilities, pushing the state-of-the-art.
  - We sustain a modest research effort with staff.
  - More typically, we partner with regional universities to host PhD students whose research topics we target to push forward the envelope of our understanding. (ODU, VT, UVA, W&M, and others)
  - We also foster SBIR projects focused on accelerator needs.

SRF Major Projects Ahead

- **12 GeV Upgrade of CEBAF**
- Facility for Rare Isotope Beams (FRIB)
  - DOE ONP@ MSU
- International Linear Collider (ILC) R&D
- Project X – proton accelerator at FNAL - *proposed*
- SNS Power Upgrade – at ORNL - *proposed*
- Compact light sources - *proposed*
- Major 4th generation light source
- High-current proton accelerators for energy production ?

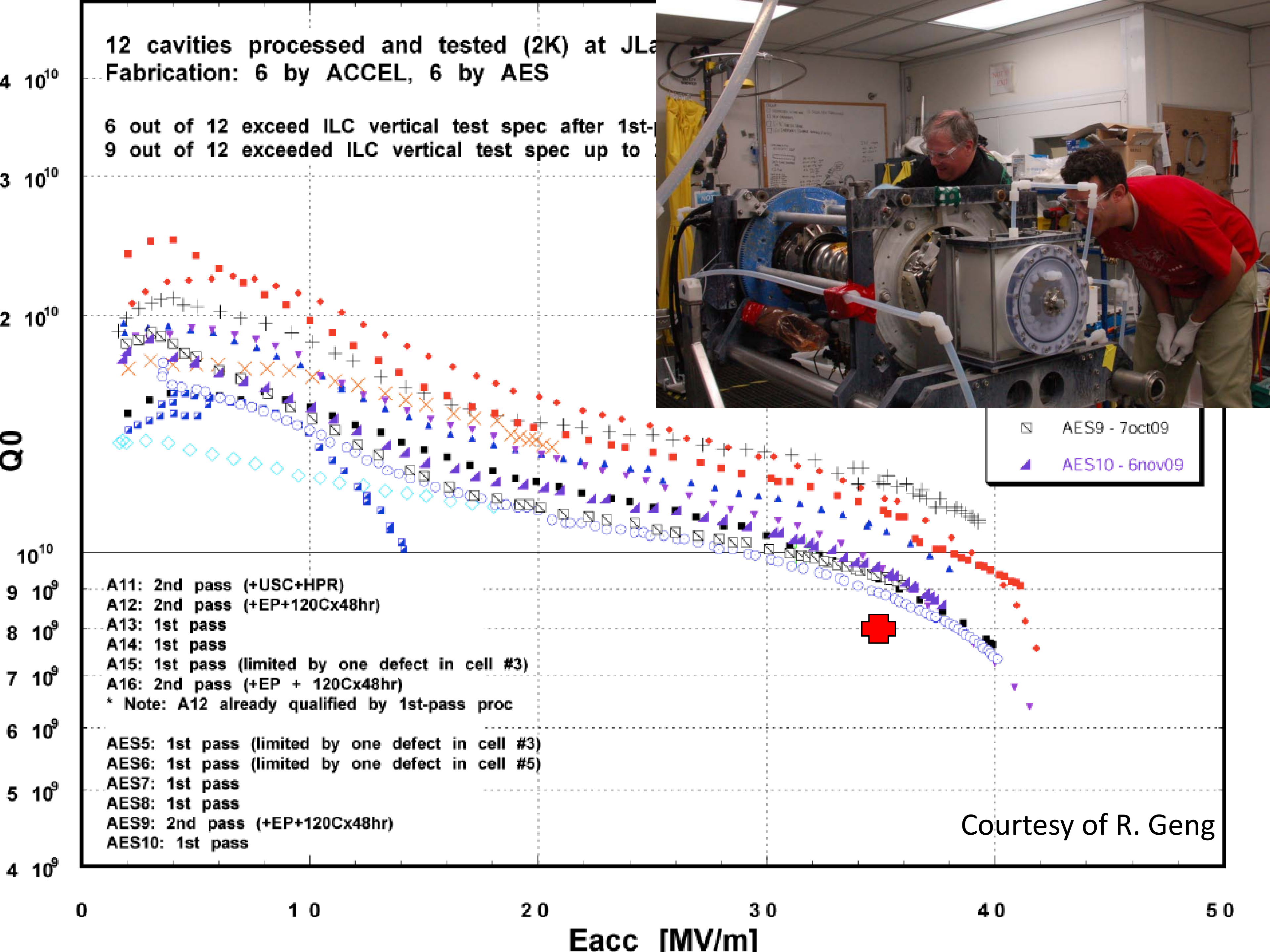
SRF R&D Highlights

Cavity R&D aimed at gradient, Q_0, current, cost

- ILC program has been very successful
  - World-leading yield rate at ILC gradient
  - Optimizing surface finishing procedures
  - Exploration of alternatives
    - Large grain material, low-loss cavity shapes, alternative processing
- Fundamental studies of materials, processes
  - Lead to progress through understanding
- Optimized structures for new requirements
  - Crab cavities (EIC), light sources (FEL), protons (EIC, SNS, Project-X, ADS), injectors
- SRF-based injectors
  - CEBAF upgrade, FELs, SRF guns, superconducting photocathodes, low-emittance injector booster

Increase gradient

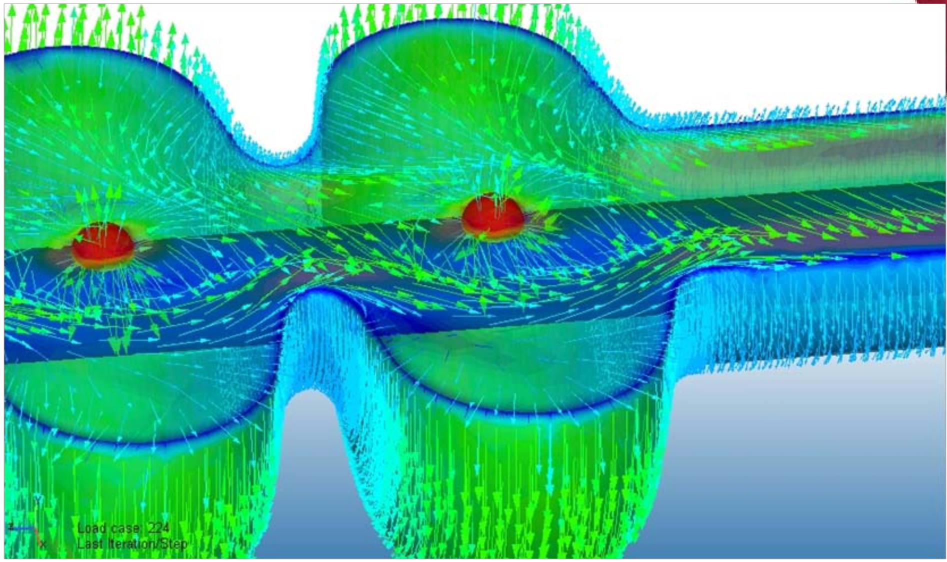
- Challenges are to push gradient to fundamental material limits, narrow the spread in performance and eliminate early failures due to material or fabrication defects or contamination
- ILC high gradient program **pushes this performance**
  - JLab provides most cavity data for the Americas region
    - Improved cleaning and assembly practices
    - Electropolishing process optimization
    - Developing next generation processing equipment
- Aim is to improve process yield through understanding
  - Quench fault location via temperature mapping
  - High-resolution optical inspection
  - Feedback on process design



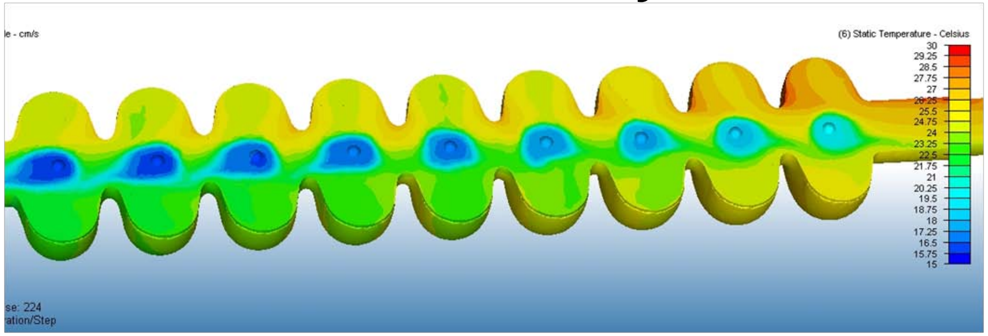
Courtesy of R. Geng

Understanding and Optimizing Electropolishing of Niobium Cavities

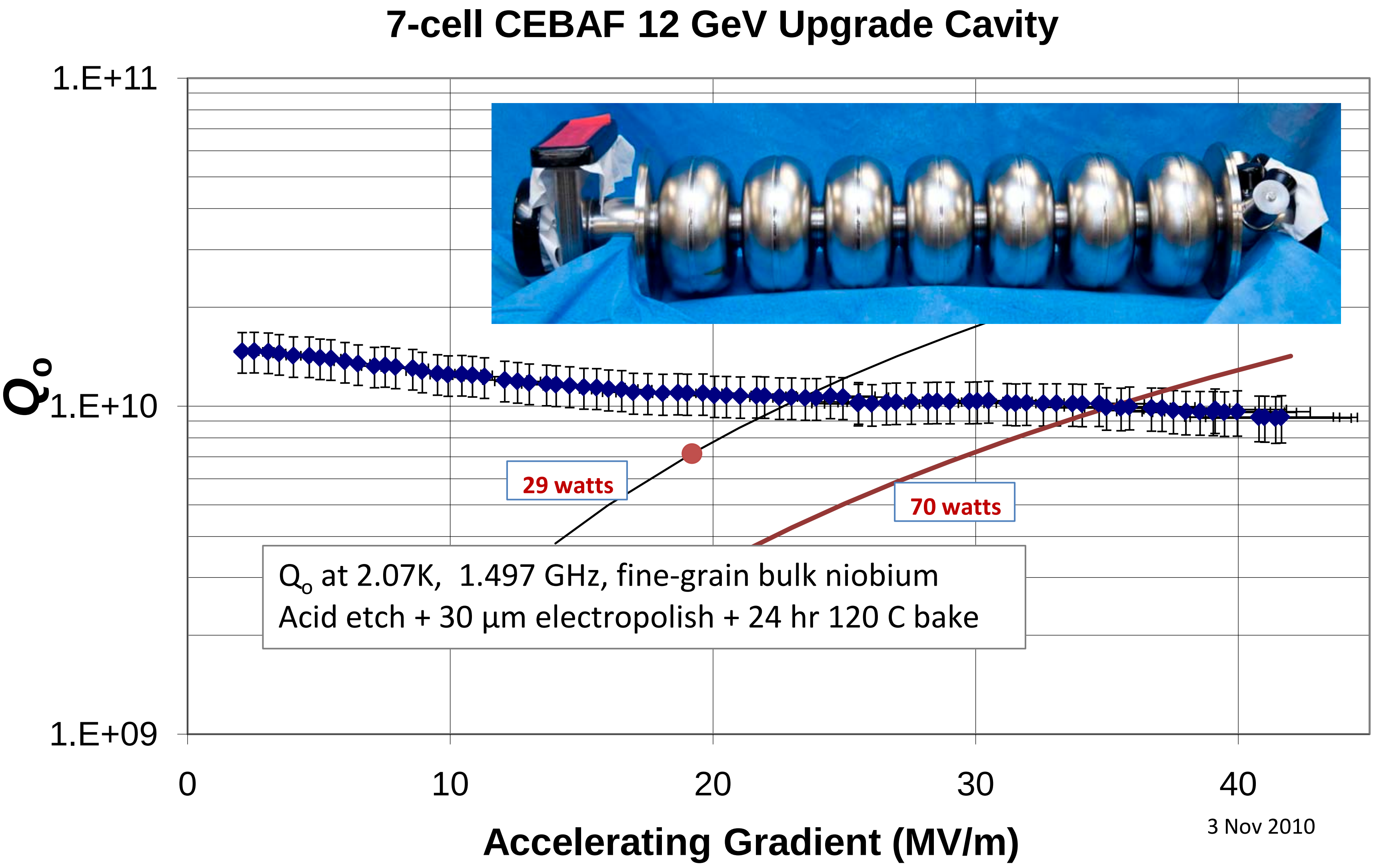
- Hydrodynamic thermal modeling reveals out-of-control temperatures(> 35C), mixing polishing *and* etching.
- Simulation models linked to experimental data.
- Feedback to cavity EP work >> "control the temperature" "move fluid slowly"
- Detailed model with measured temperature-dependent viscosity and F^- diffusion coefficient
- Using these tools to engineer more efficient cavity polishing systems (e.g., ICP with VEP)



Internal flow dynamics



Temperature variations



7-cell CEBAF 12 GeV Upgrade Cavity
1.E+11
1.E+10
1.E+09
Qo
0
10
20
30
40
Accelerating Gradient (MV/m)
29 watts
70 watts
Qo at 2.07K, 1.497 GHz, fine-grain bulk niobium
Acid etch + 30 µm electropolish + 24 hr 120 C bake
3 Nov 2010

The path towards higher Q_0

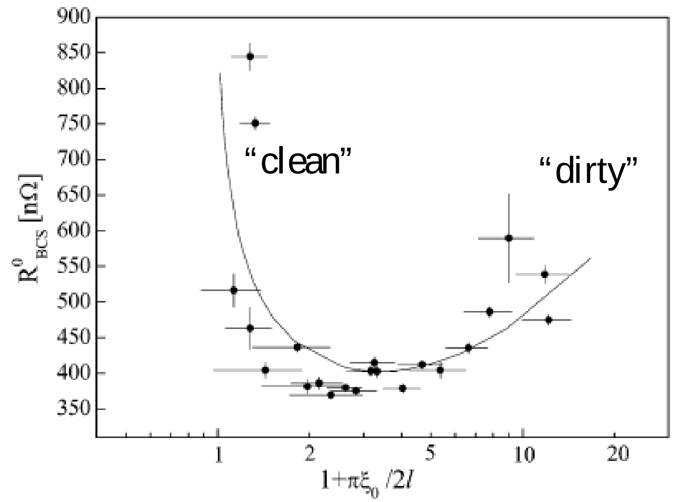
- Short-term:
  - Fully exploit the superconducting properties of bulk Nb for operation at $\leq$ 2 K
- Long-term:
  - Develop new superconducting materials for RF applications and operation at 4.3 K

How can we improve the Q_0?

Let's assume the cavity frequency is fixed

- Decrease operating temperature
- Increase magnetic shielding around the cavity

- Tune impurity concentrations at the Nb surface to
  - Minimize R_{BCS}



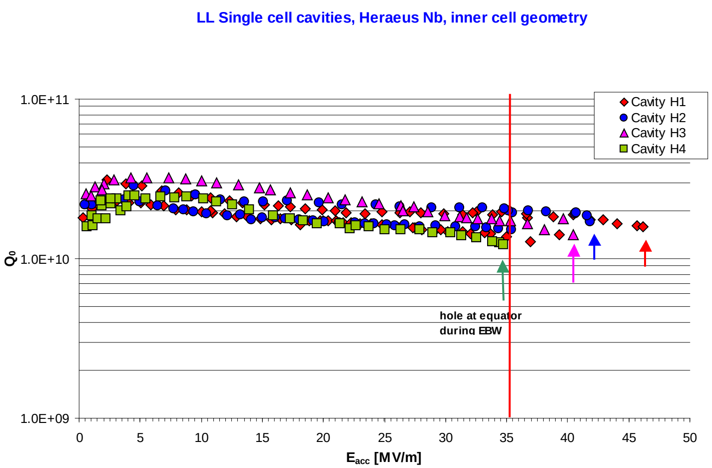
BCS resistance of Nb at 1.5 GHz, 4.2 K

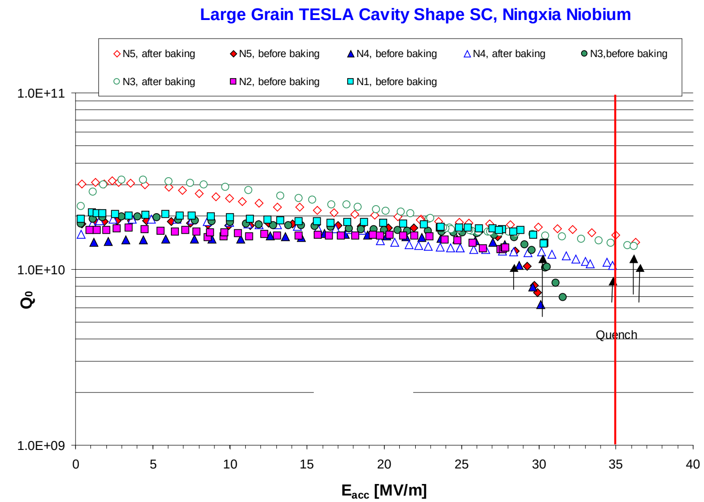
Possible improvement by a factor ~ 2

  - Minimize R_{res}

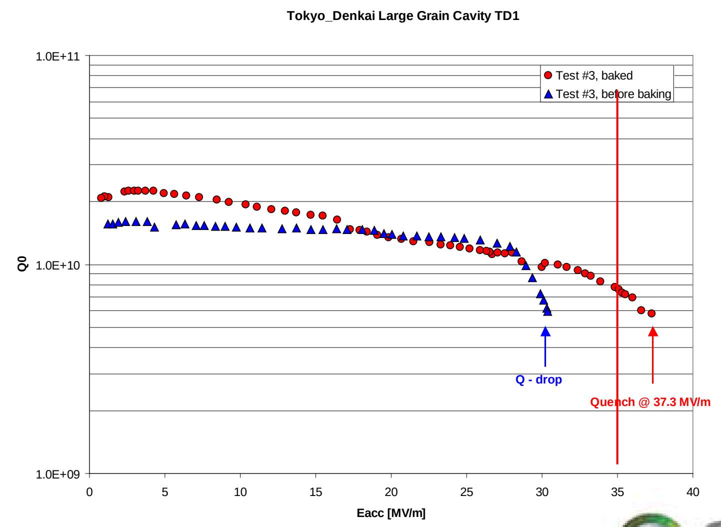
Large grain/Single Crystal Niobium

- Reproducibility Tests with single-cell cavities from large grain niobium of different manufacturers





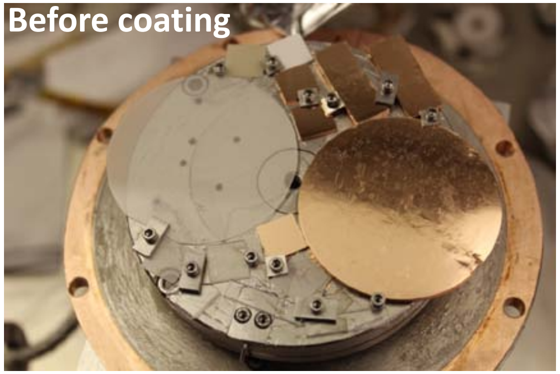
- Qualification of new vendor (Tokyo Denkai)
- Exploration of “rolled single crystal” (w. DESY)
- Continued work on 9-cell cavities
  - Barrel polishing/guided repair
  - 2 new LG LL cavities in fabrication

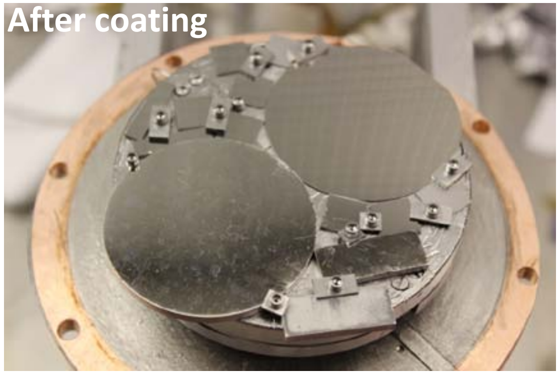


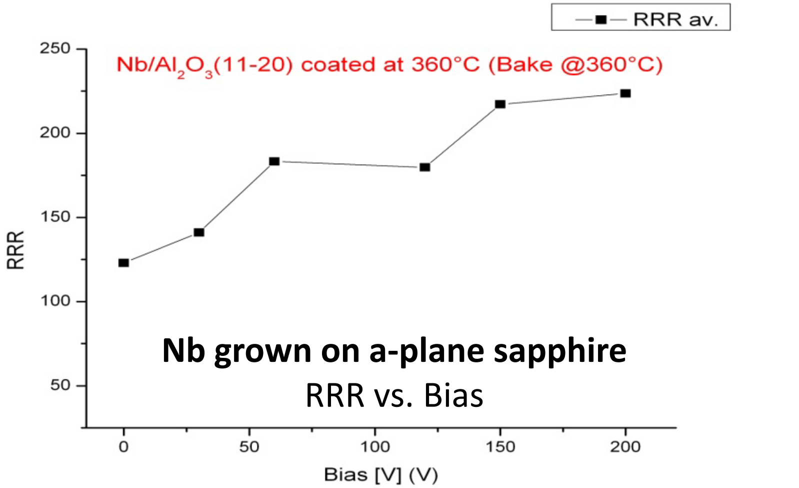
Towards “bulk-like” Nb films

Energetic Deposition via Electron Cyclotron Resonance

Cu substrates (large grain, fine grain, single crystals) Sapphire & MgO single crystal , AlN & Al2O3 ceramic, fused silica







Bake Temp.	Coating Temp.	Bias [V]	Al_2O_3 (11-20)
360°C	360°C	-120	**179.8**
360°C	500°C	-120	189
700°C	360°C	-120	**348**
500°C	360°C	-120	348
500°C	500°C	-120	**488**

Nb grown on a-plane sapphire (Bias -120V)
RRR vs .Bake & Coating Temp.

Bake Temp.	Coating Temp.	Bias [V]	Nb/Cu_{fg}
360°C	360°C	-0	51
360°C	360°C	-90	68
360°C	**360°C**	**-150**	**82**
LEP 2			**10**

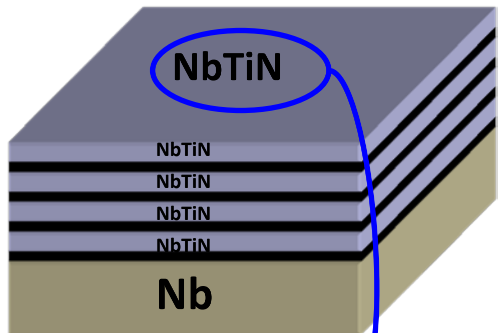
Nb grown on fine grain Cu
RRR vs. Bias

Coating on Cu half cell to check plasma conformality

NbTiN films for multilayer structures

UHV Multi-Technique Deposition System

Development of alternative SRF materials for multilayered structures (Gurevich concept)

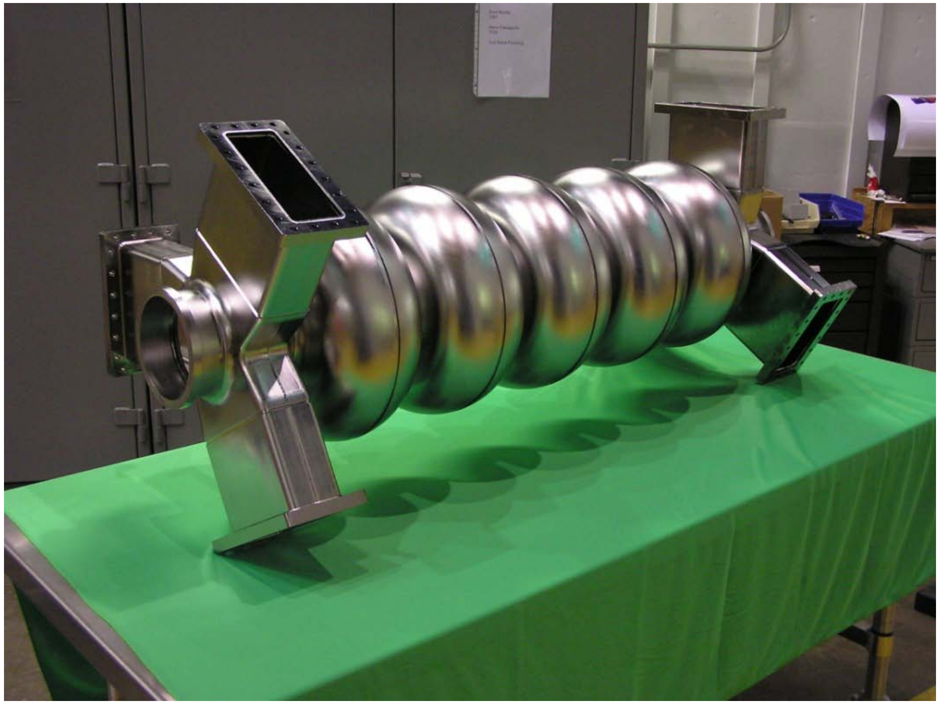


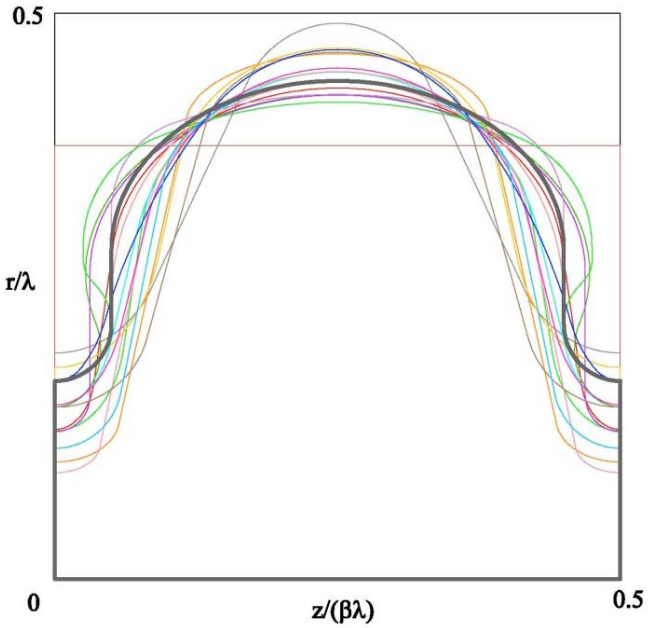
Reactive sputtering, Target Nb 80%/Ti20%, N_2/Ar= 17% -Pre-treatment, coating & annealing 4hours@ 600^{o}C

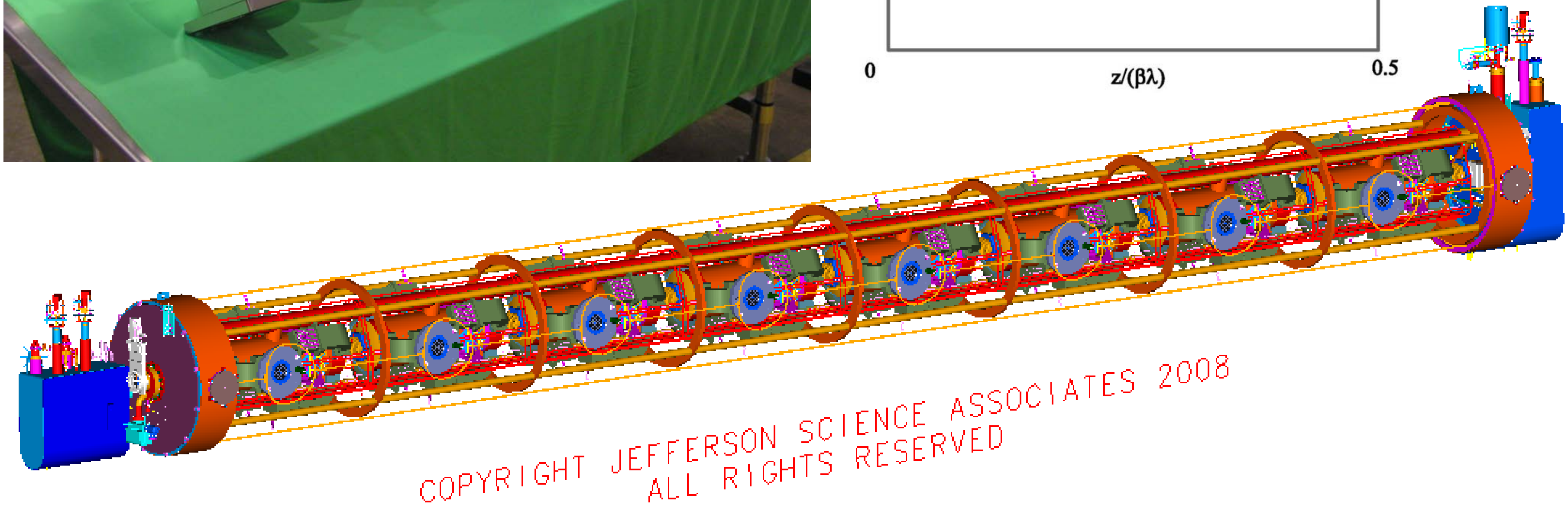
				Ant. Thickness [nm]	Al_2o_3 (11-20)		MgO (100)		AlN (0001)/ Al_2o_3		AlN ceramic	
					T_c	ΔT_c	T_c	ΔT_c	T_c	ΔT_c	T_c	ΔT_c
23	600°C	600°C	**30'**	600	**15.33**	0.45	16.14	0.48	**14.69**	0.23	13.97	0.87
25	600°C	600°C	**10**	200	**15.43**	0.45	**16.1**	0.65	**14.19**	0.09	12.91	0.26
24	600°C	600°C	**5'**	100	**15.04**	0.24	**14.58**	0.94	**14.76**	0.18	13.58	0.09

750 MHz 8-cavity Cryomodule

Cavity shape optimized to minimize higher order modes





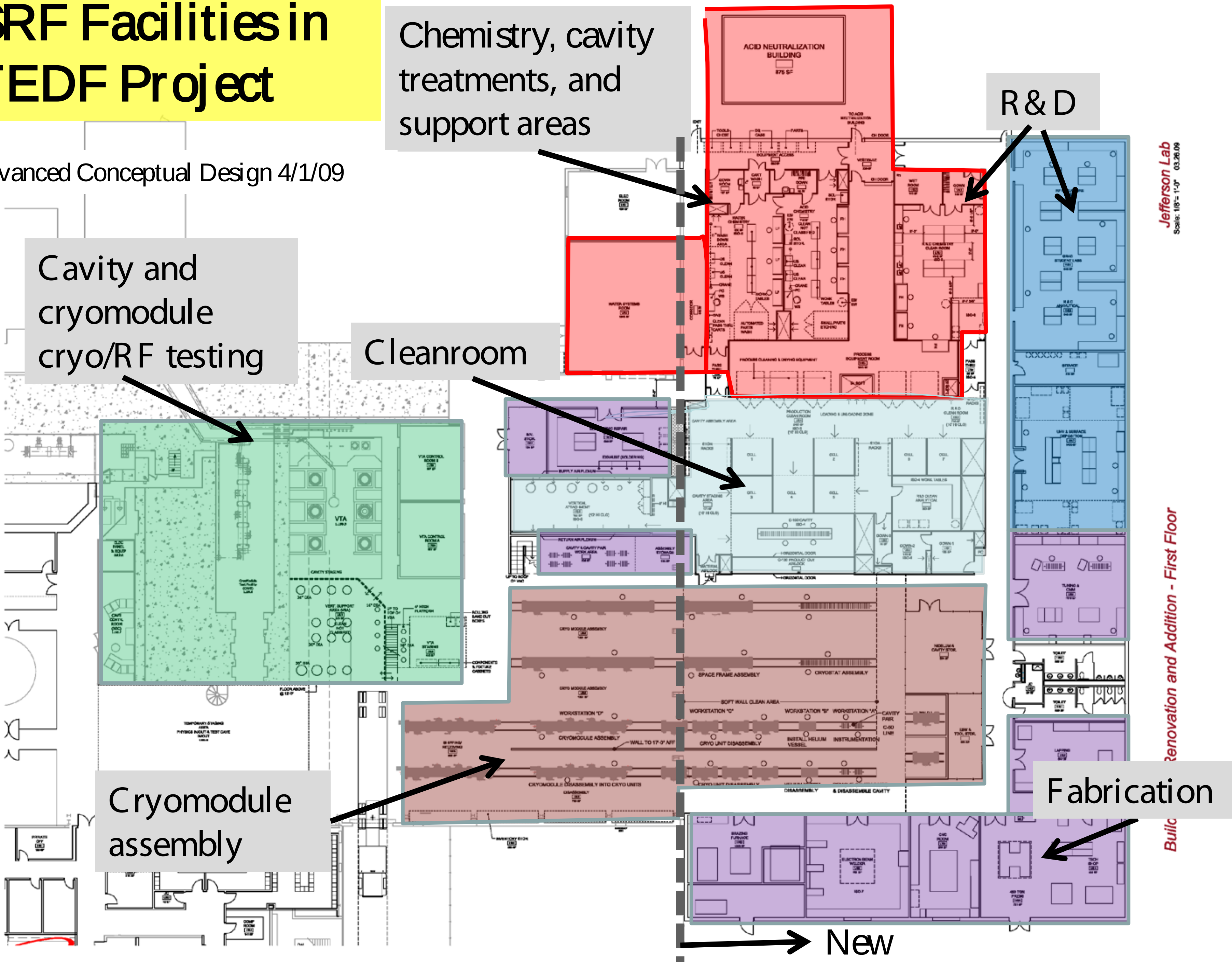


SRF Renovation Plan

- Anticipating the need to respond strongly to the growing number of applications, we have developed a business plan based on restoring original CEBAF SRF capacity with state-of-the -art infrastructure – manufacturing (~75%) and R&D (~25%)
- Production capacity equivalent to:
  - 2 cryomodules per month
  - 16 multi-cell cavities per month
- The new “TEDF” Building is designed around this capacity

SRF Facilities in TEDF Project

Advanced Conceptual Design 4/1/09



JLab SRF in Summary

- State-of-the-art manufacturing, processing and testing facilities for SRF cavities
  - Now launched into the **CEBAF 12 GeV Upgrade**
  - Consulting with others on future projects
- World class R&D projects:
  - Cavity design and simulation (high current)
  - Material development (large-grain Nb, thin films)
  - Surface processing (electropolishing)
  - Basic SRF physics (understanding anomalous RF losses)

Reduce cost and improve reliability of SRF accelerators worldwide