High Current Superconducting Linac for Accelerator Driven Systems

Andrew Hutton, Associate Director

Jefferson Lab, Virginia

Jefferson Lab and SRF

Jefferson Lab

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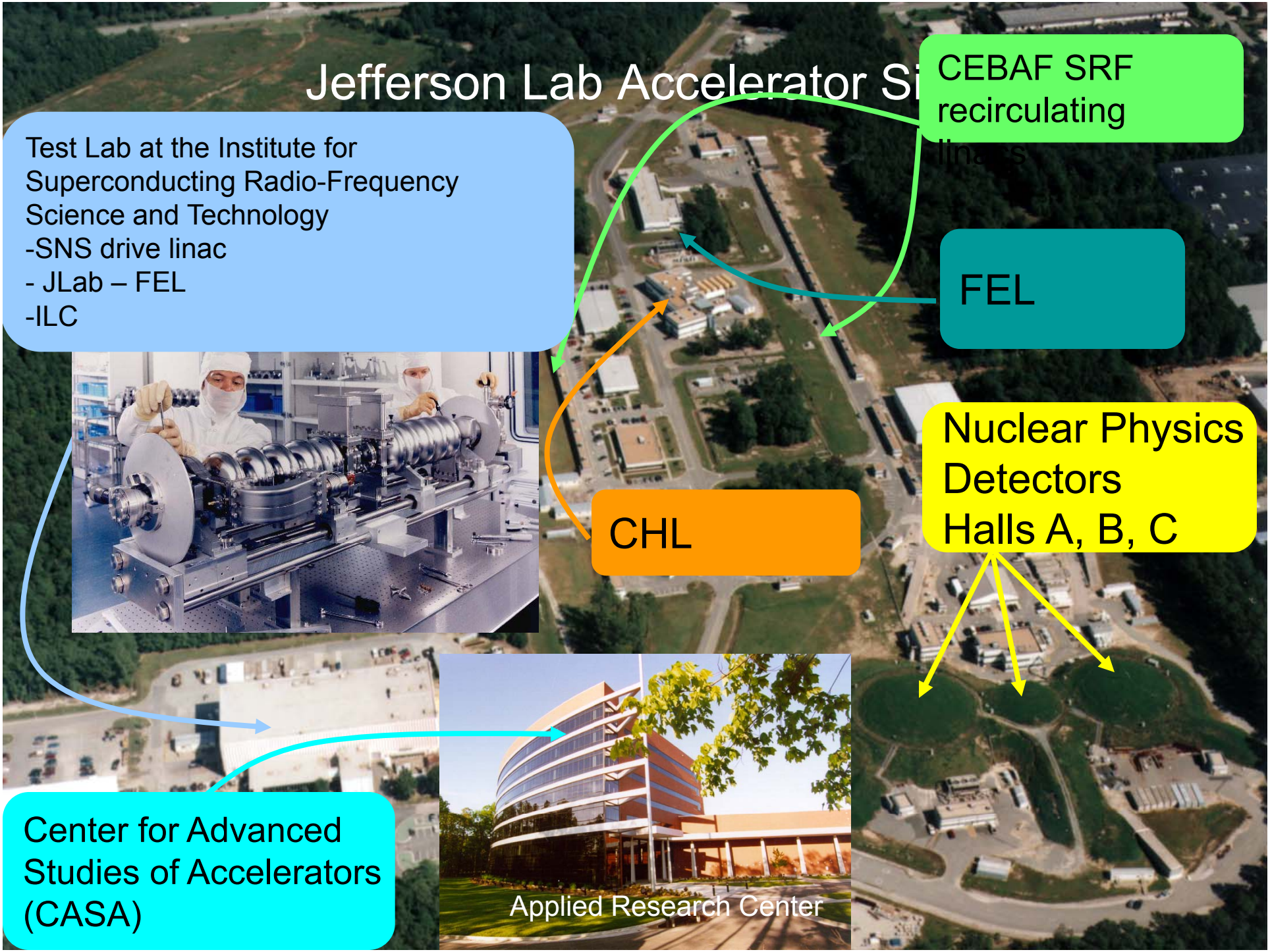
Jefferson Lab

Jefferson Lab (JLab)

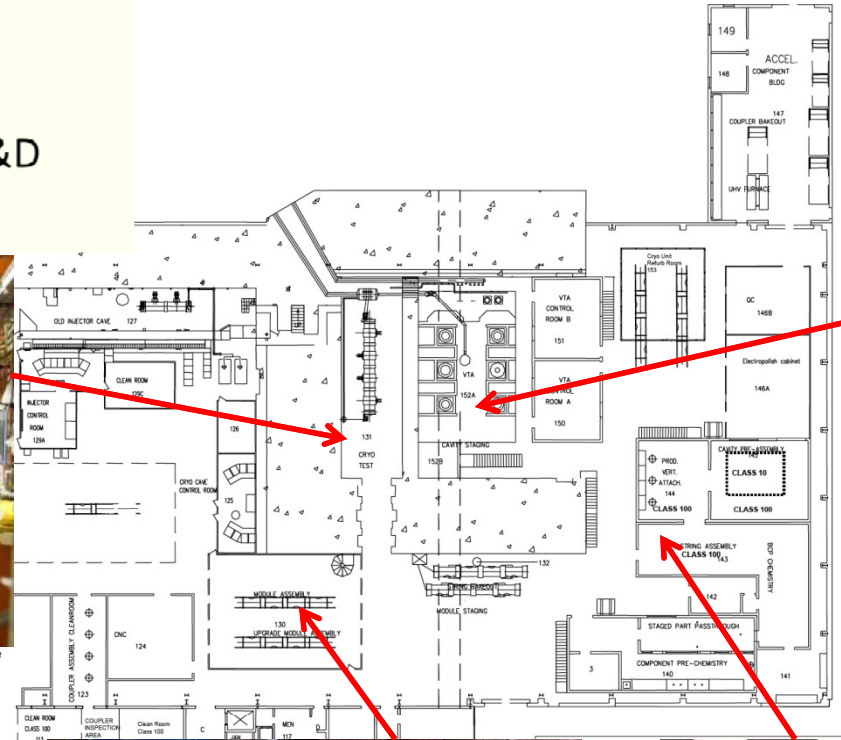
- DOE National Laboratory founded 25 years ago for fundamental Nuclear Physics research
  - Quarks, gluons . . . . .
- Primary research tool is the Continuous **Electron** Beam Accelerator
  - First large-scale use of superconducting radiofrequency (SRF) technology
  - Initially a 4 GeV, **1 MW** beam, it currently operates at 6 GeV
    - Upgrade to 12 GeV is funded and under construction
- JLab built the superconducting cavities for the world's highest power **proton** linac for the Spallation Neutron Source (SNS) at Oak Ridge national Laboratory


Jefferson Lab Accelerator Si
CEBAF SRF recirculating linacs
Test Lab at the Institute for Superconducting Radio-Frequency Science and Technology
-SNS drive linac
- JLab – FEL
-ILC
FEL
CHL
Nuclear Physics Detectors Halls A, B, C
Applied Research Center
Center for Advanced Studies of Accelerators (CASA)

JLab Institute for Superconducting RF Science and Technology

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

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



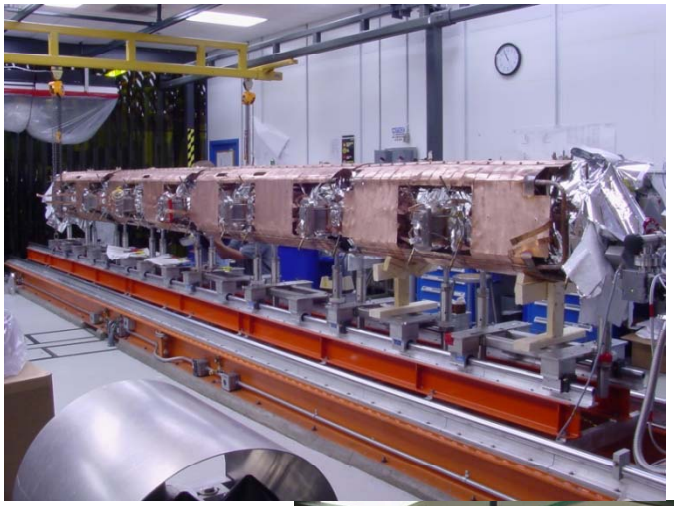
JLab SRF Experience

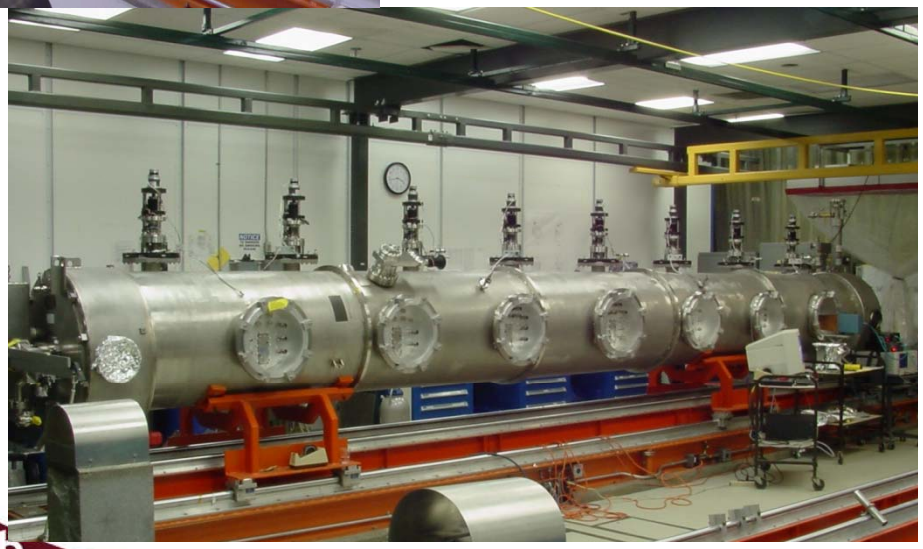
- The SRF Institute has fabricated and/or processed a wider variety of multi-cell SRF cavities than anyone else
- 87 cavities fabricated / >650 multi-cell cavities processed
  - 26 different cavity types processed
- In addition, a large number of smaller test cavities have been fabricated and/or processed for materials and processes R&D
- >3200 individual cryogenic cavity tests since 1991
- Assembled and delivered 82 completed cryomodules
  - 43 for CEBAF
  - 4 for JLab FEL
  - 23 for SNS @ ORNL
  - 2 for others
  - Refurbished 10 cryomodules for CEBAF

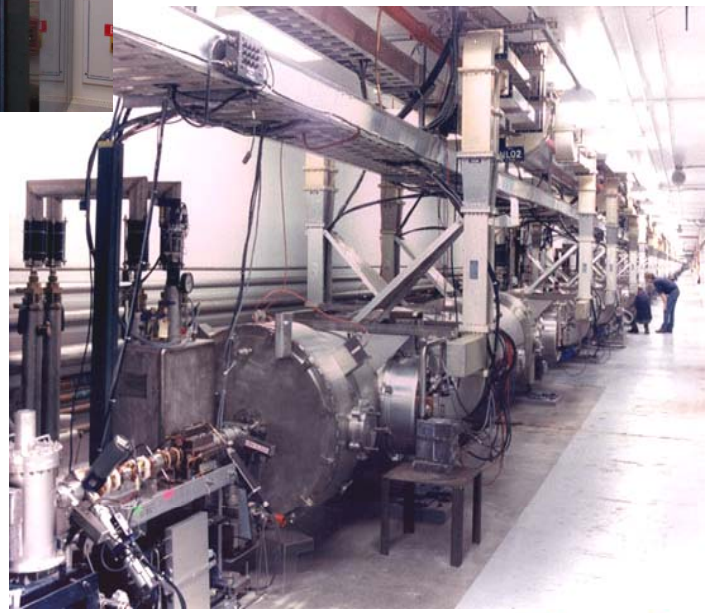
JLab Multicell Nb Cavity Experience

Project	# of Cavities built @ Jlab	# of Cavities processed / tested	Frequency (MHz)	Beta	# of Cells	Duty Factor
CEBAF (OC cell shape)	20	358	1497	1	5	CW
CEBAF (OC) - C50 rework		94	1497	1	5	CW
CEBAF Upgrade Style (OC)	8	8	1497	1	7	CW
CEBAF Upgrade Style (LL)	5	5	1497	1	7	CW
CEBAF Upgrade Style (HG)	9	11	1497	1	7	CW
C100 - (LL)	4	4	1497	1	7	CW
FEL IR DEMO (OC)	10	10	1497	1	5	CW
FEL 10 kW Upgrade (OC)	8	8	1497	1	7	CW
FEL HCCM (HC)	3	1	1497	1	5	CW
FEL HCCM (HC)	1		750	1	5	CW
AES HC Inj		3	750	1	1	CW
AES HC Inj		1	1500	1	1	CW
APT	2	2	700	0.64	3	CW
APT		3	700	0.64	5	CW
SNS	4	47	805	0.61	6	Pulsed
SNS	1	52	805	0.81	6	Pulsed
RIA	2	2	805	0.47	6	Pulsed
INFN Legnaro - seamless		1	1500	1	5	CW
INFN Milan - TRASCO		1	703	0.5	5	CW
DESY - seamless		3	1300	1	2	CW
KEK	1	1	1300	1	10	Pulsed
ILC-like - superstructure	1	1	1497	1	10	Pulsed
BNL		1	704	1	5	CW
FLASH - FNAL/DESY	5		3900	1	9	Pulsed
Rossendorf - Inj	2		1300	1	2.5	CW
PKU 3.5 cell Inj		1	1300	1	3.5	CW
ILC - (TESLA)		22	1300	1	9	Pulsed
ILC - (LL)	1	1	1300	1	7	Pulsed
ILC - (Japan LL)		2	1300	1	9	Pulsed
ILC - (TESLA)	4	4	1300	1	9	Pulsed

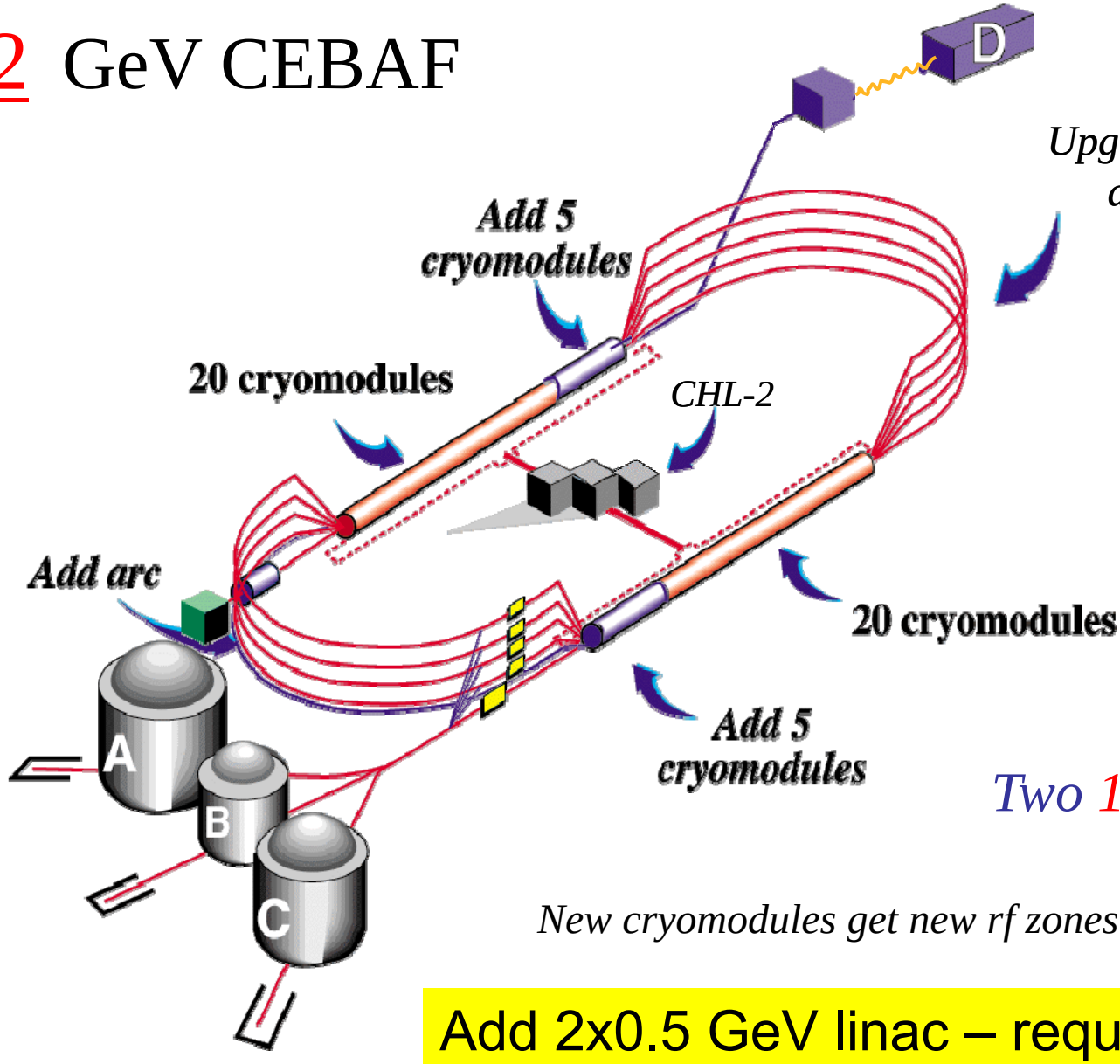
SRF Photo gallery







12 GeV CEBAF



Upgrade magnets and power supplies

Two 1.1 GV linacs

New cryomodules get new rf zones

Add 2x0.5 GeV linac – requires new 4.5kW refrigerator (~6MW)

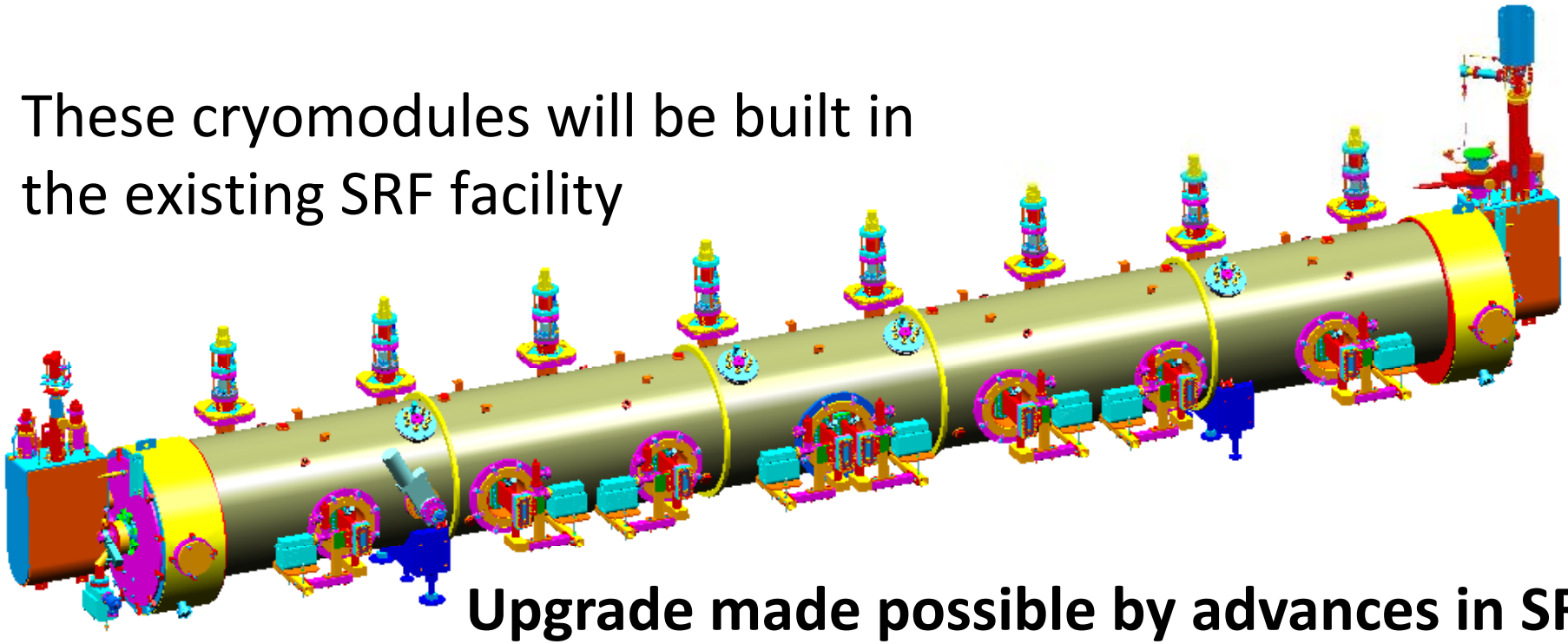
CEBAF Upgrade Cryomodule

108 MV, 20 MV/m, 7-cell cavities

Compare with original CEBAF cryomodule specification

20 MV, 5 MV/m, 5-cell cavities

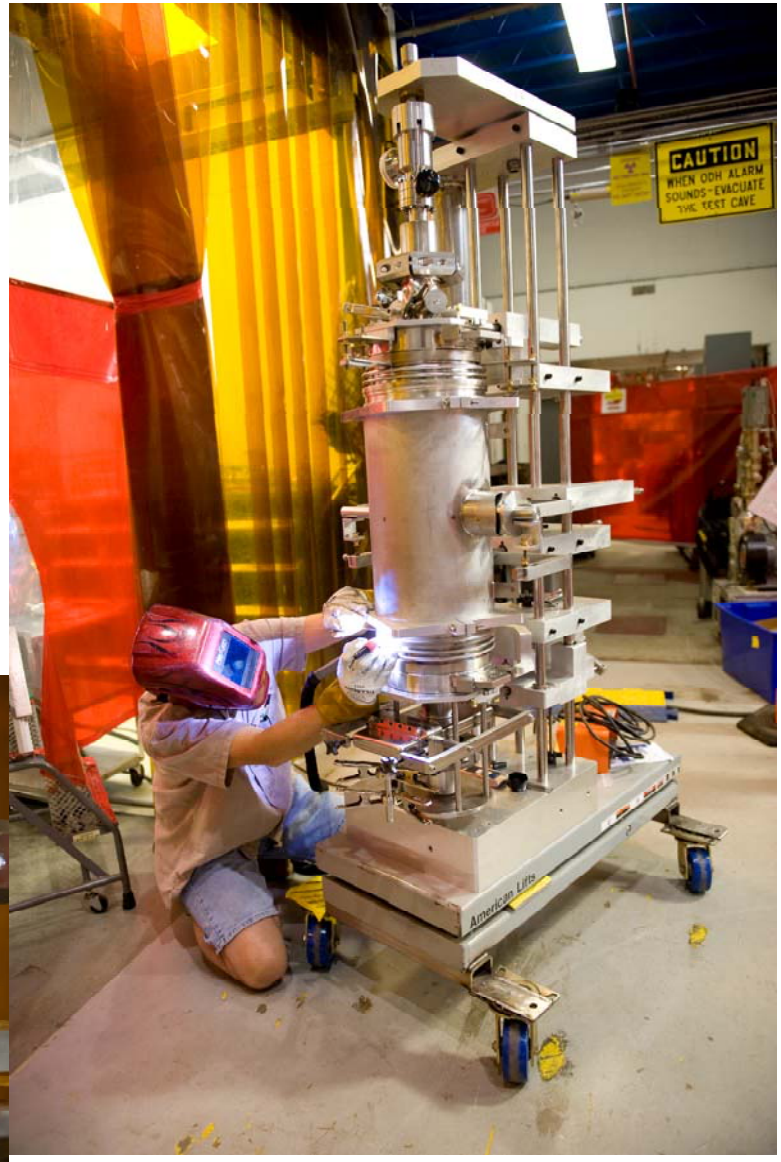
These cryomodules will be built in the existing SRF facility



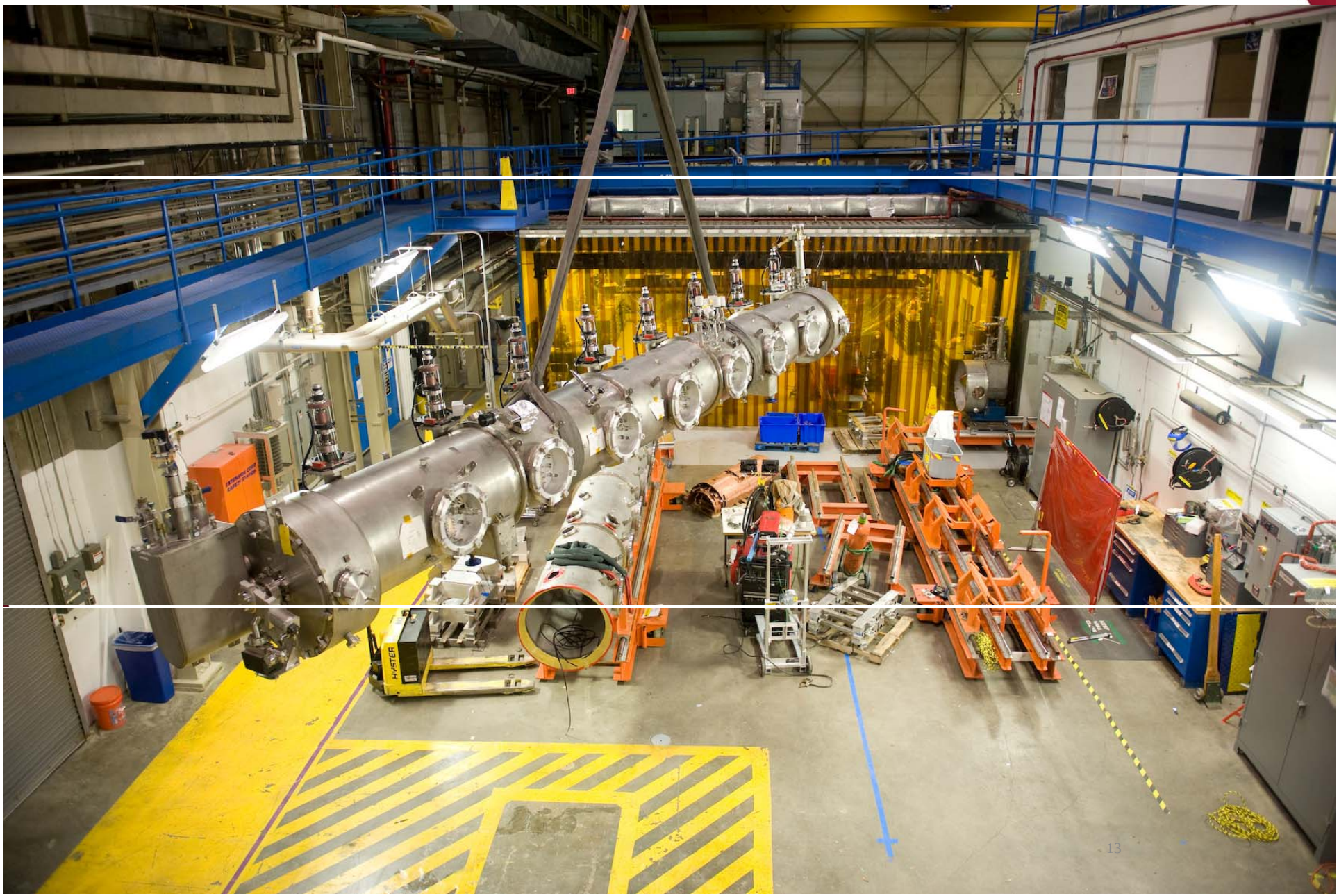
Upgrade made possible by advances in SRF

Prototype C-100 Cavity

- Testing welding jig for 12 GeV Upgrade Helium vessel
  - Found problem with magnetization of Helium vessel
  - We will be re-ordering parts to maintain high Q



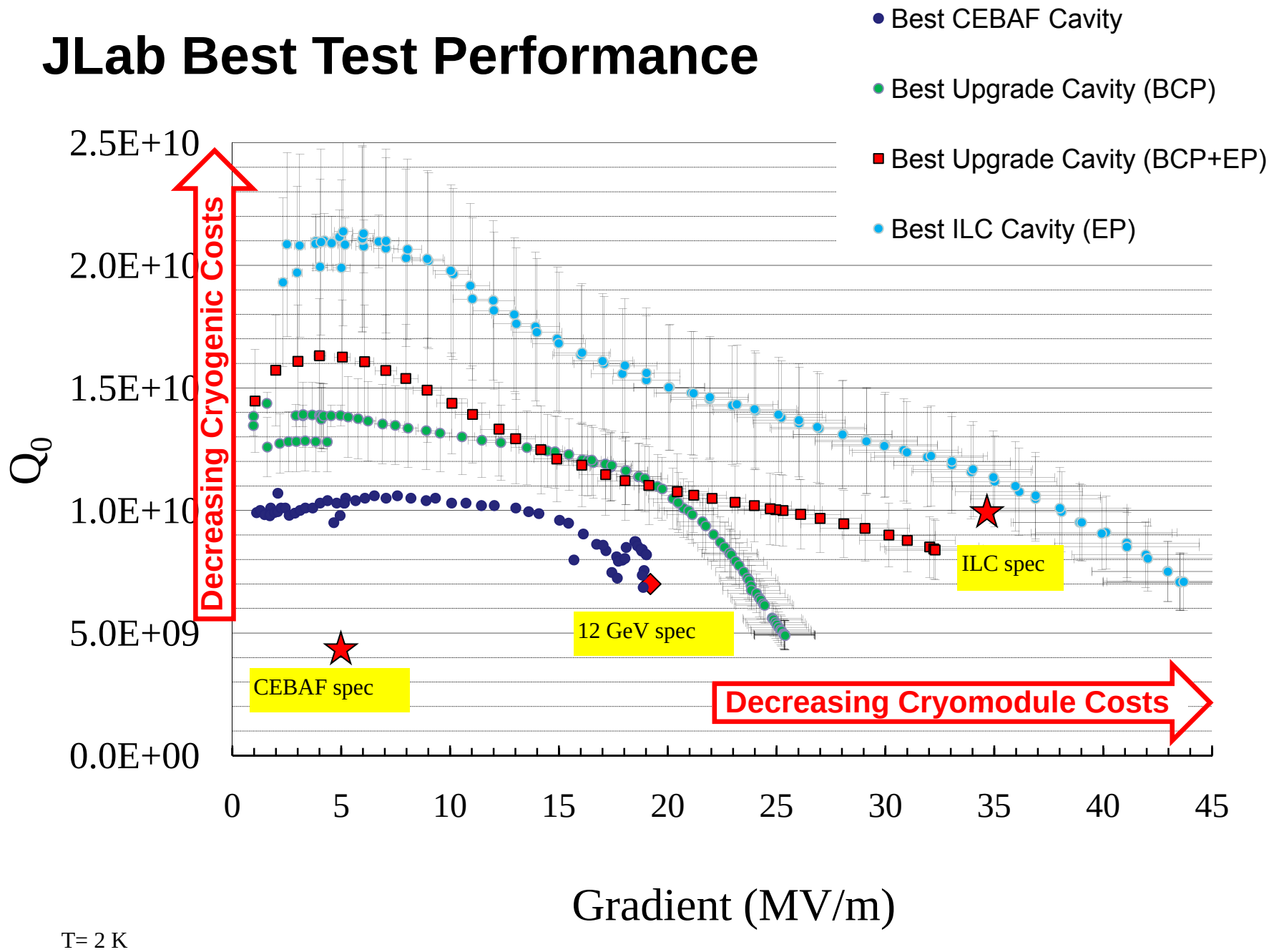
Prototype C-100 Cryomodule



R&D to Increase the Gradient

- Higher gradients reduce cost of tunnel and equipment
- 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
- International Linear Collider (ILC) has funded an R&D program to increase this performance
  - JLab provides most of the cavity data for the Americas region
    - Improved cleaning and assembly practices
    - Electro-polishing process optimization
    - Developing next generation processing equipment
- Results are being applied to all superconducting cavities

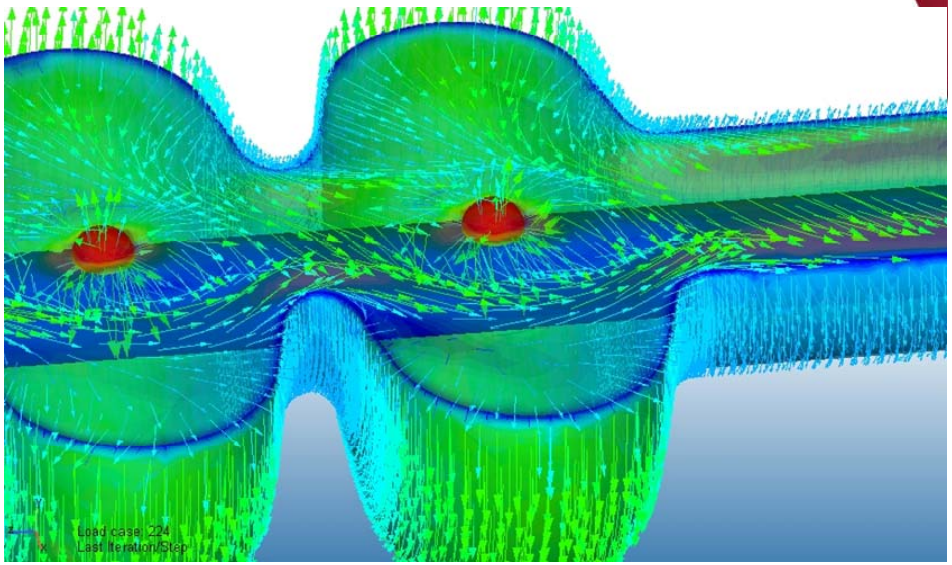
JLab Best Test Performance



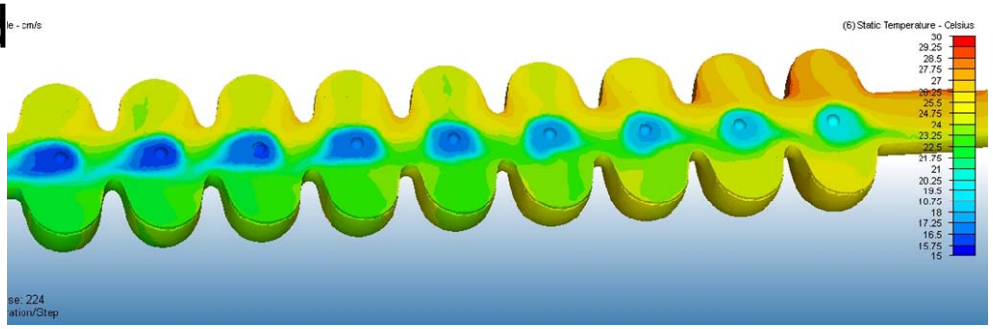
T= 2 K

Understanding electropolishing

- Hydrodynamic thermal modeling reveals out-of-control temperatures(> 35° C), 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)



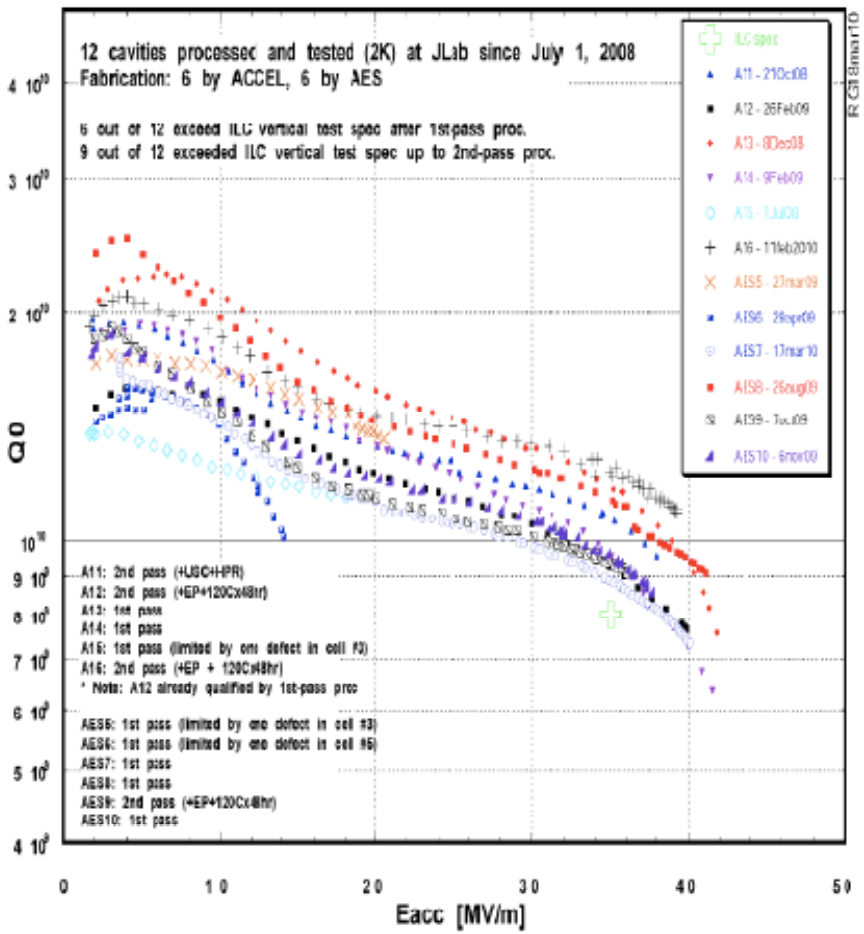
Internal flow dynamics

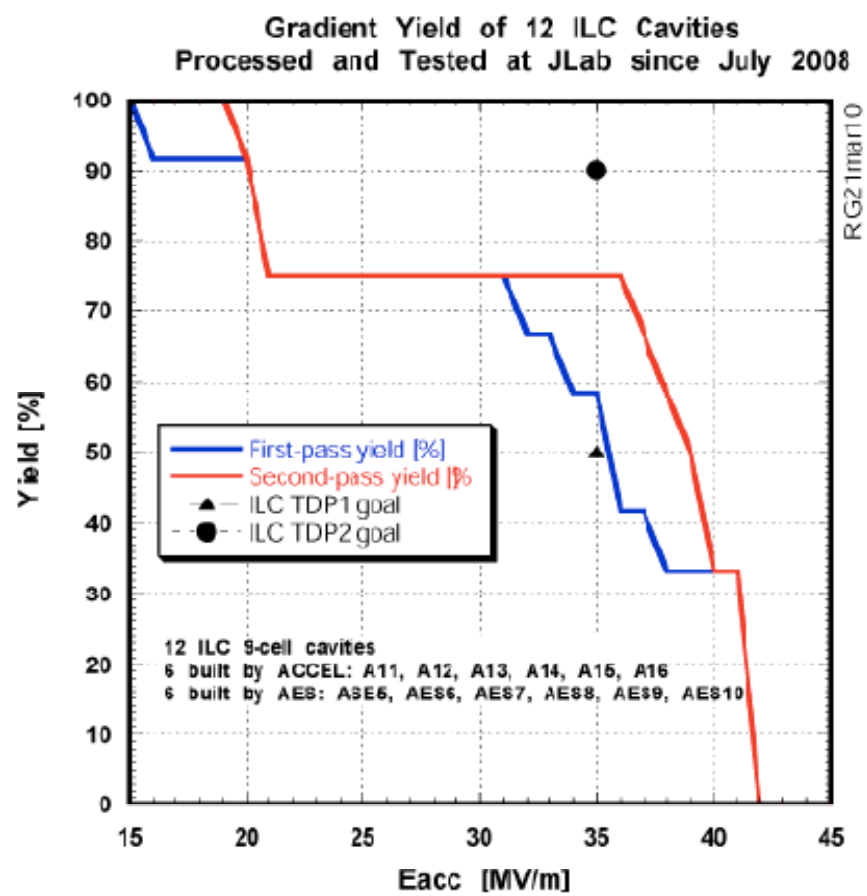


Temperature variations

Most Recent 9-cell Results at JLab

6 cavities built by ACCEL and 6 by AES





The path towards higher Q_0

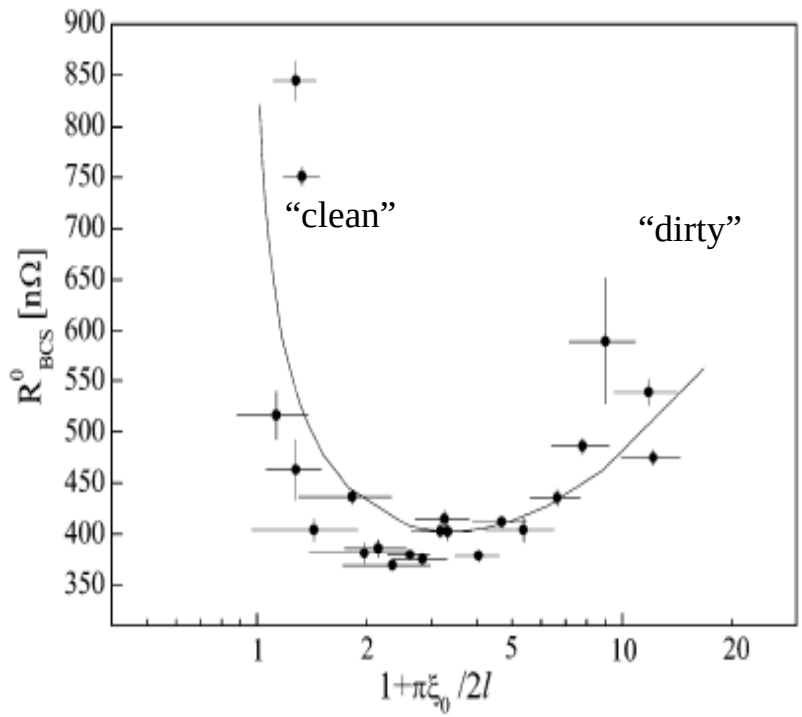
- Present day
  - Follow established rinsing procedures to eliminate field emission
- Short-term:
  - Fully exploit the superconducting properties of bulk Niobium for operation at $\leq$ 2 K
- Long-term:
  - Develop new superconducting materials for RF applications and operation at 4.5 K

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}
  - Minimize R_{res}

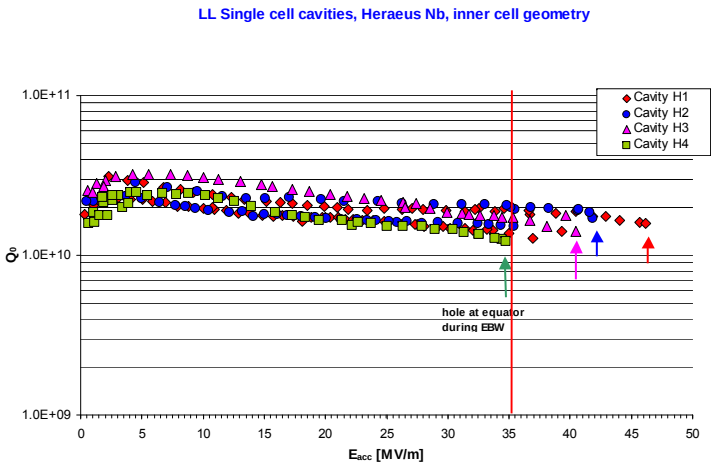


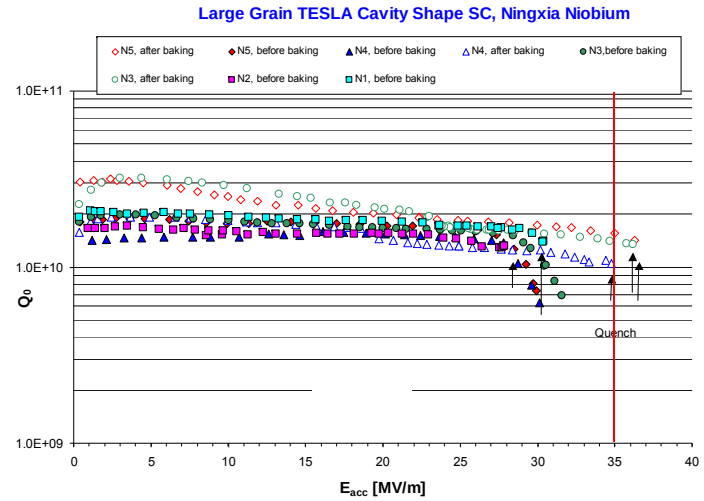
BCS resistance of Nb at 1.5 GHz, 4.2 K

Possible improvement by a factor ~ 2

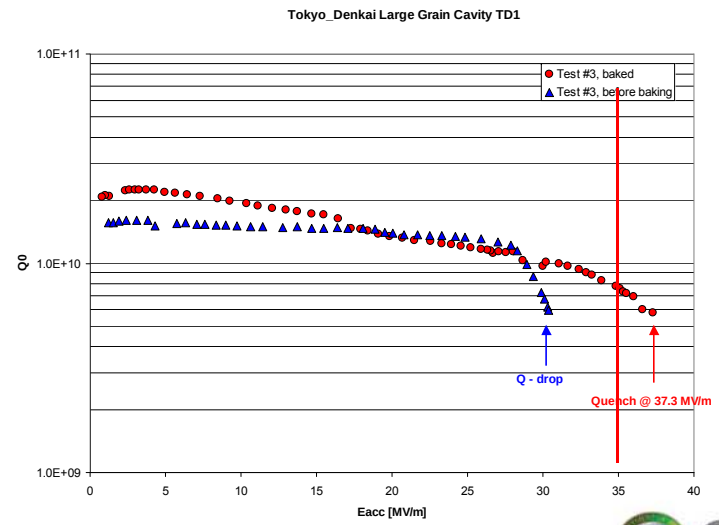
Large grain/Single Crystal Niobium

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





- Qualification of several vendors
- Exploration of "rolled single crystal" (w. DESY)
- Continued work on 9-cell cavities
  - Barrel polishing/guided repair
  - 2 new LG LL cavities in fabrication



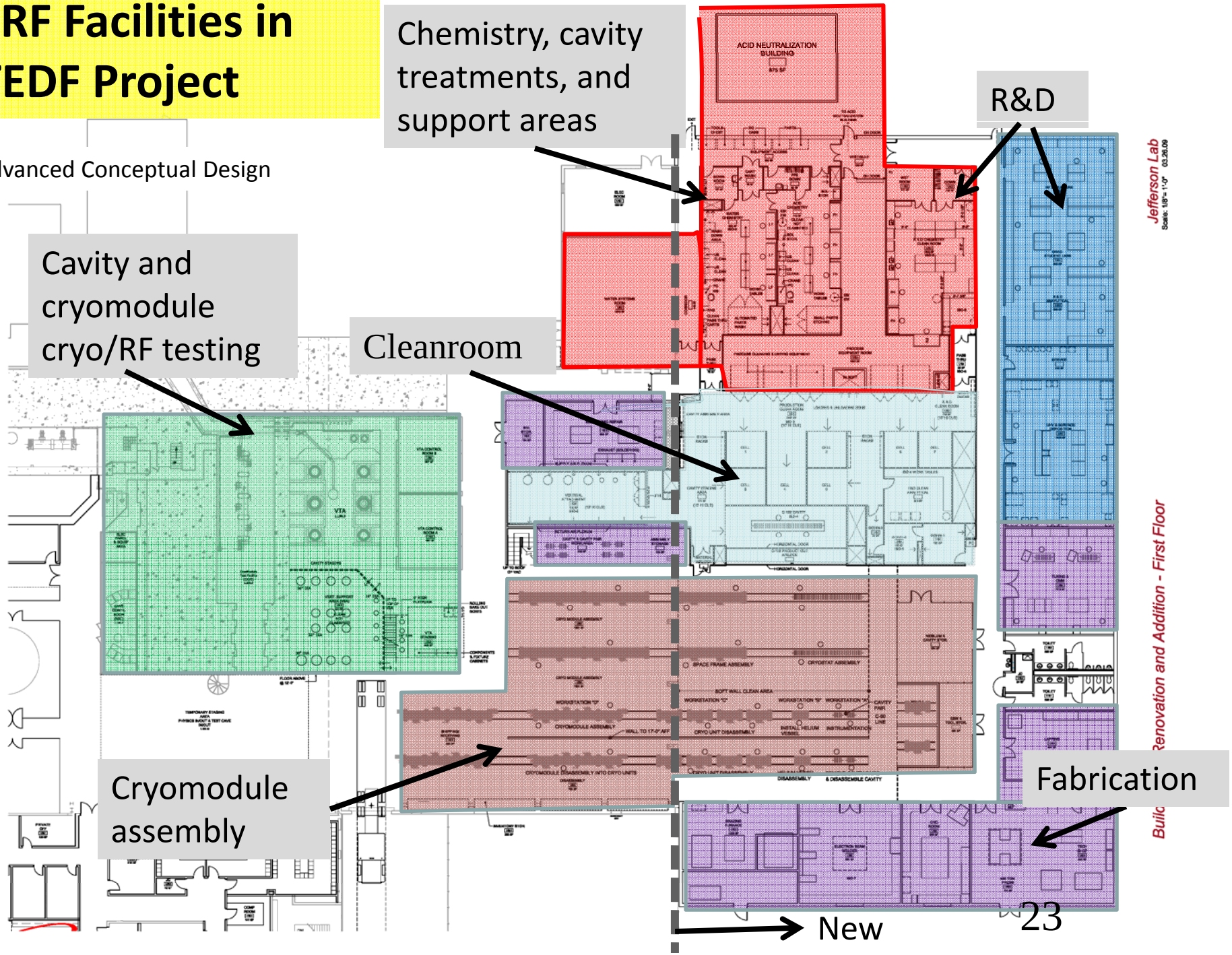
TEDF – Technology and Engineering Development Facility

- We have developed a business plan based on restoring original CEBAF SRF capacity – manufacturing (~75%) and R&D (~25%)
- Production capacity equivalent to:
  - 2 cryomodules per month
  - 16 multi-cell cavities per month
- New TEDF Building is designed around this capacity

Test Lab Renovation Has Started

SRF Facilities in TEDF Project

Advanced Conceptual Design



Proton Accelerators

With thanks to Bob Rimmer

Jefferson Lab

Challenges in high power SRF for Protons

- CW SRF requires a lot of cryogenic capacity
  - E.g. SNS 1 GeV requires 4.5 kW Liquid Helium Plant
- High average currents require a lot of RF power
  - E.g. 10 mA x 2 GeV = 20 MW
- High RF power requires robust couplers
  - E.g. 20 MW ÷ 200 cavities = 100 kW/coupler
  - (SNS couplers good for ~200 kW, 1 MW windows OK)
- High average current may require instability control
- Beam losses could spoil everything

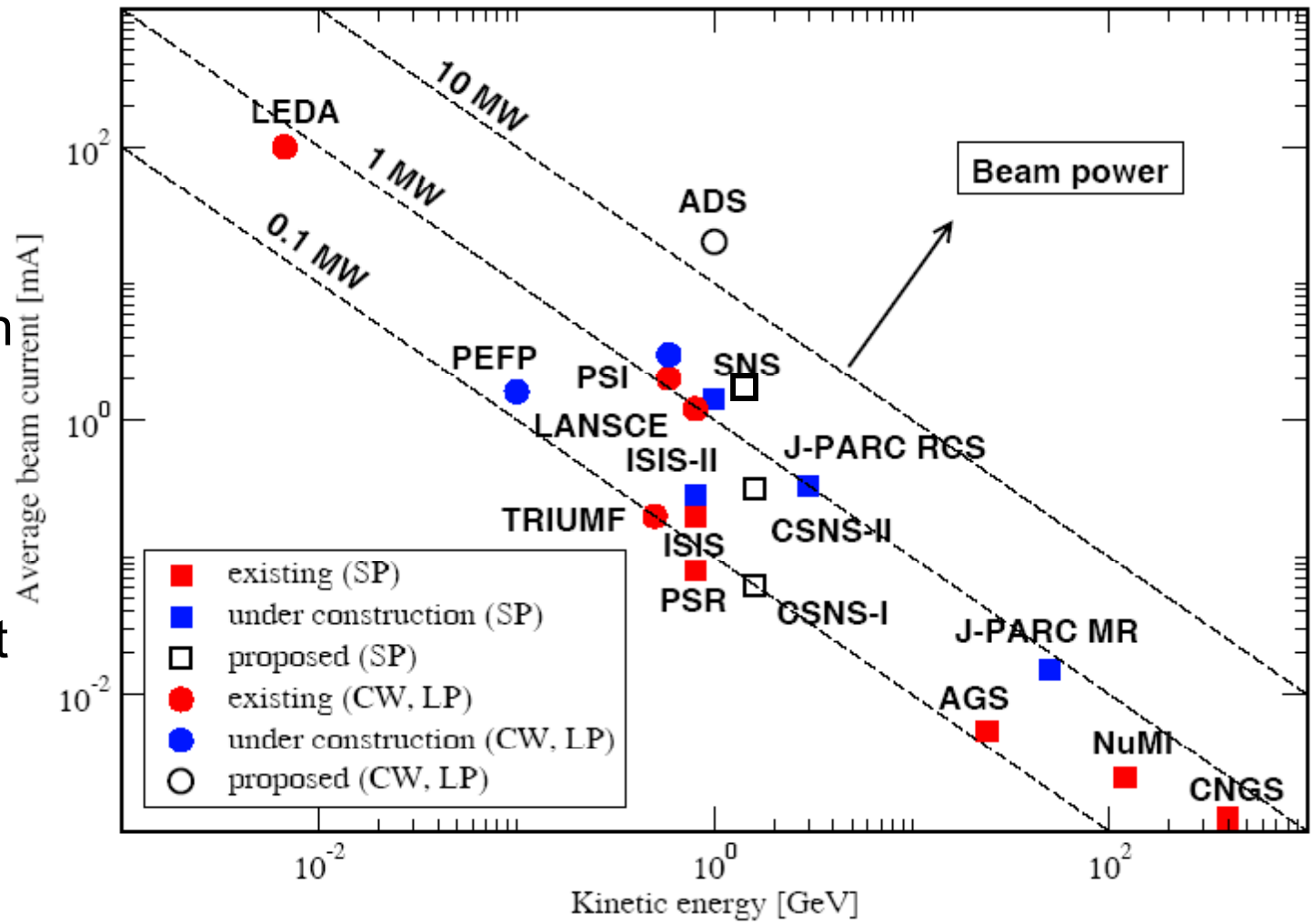
The Good News

- Large CW SRF facilities operate well (CEBAF, LEP, etc...)
- "Proton Driver" cavities are in development
  - ANL, TRIUMF, JLab, KEK, …
- Cavity performance continues to improve (E_{acc} and Q_o)
- Instability limits and mitigations are well understood
- Large 2K cryogenic plants are getting more efficient
  - JLab leads the world in cryogenics
    - Linde has licensed JLab patents world-wide for existing and future cryogenic plants
- New CW RF sources continue to be developed

Beam Power Frontier for Protons

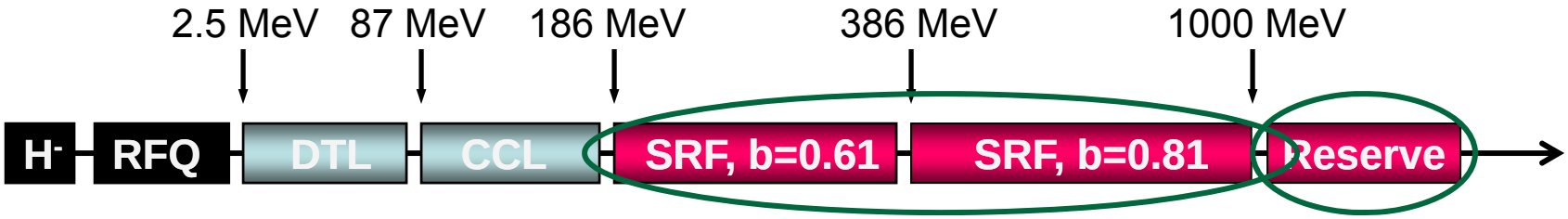
Central challenge at the beam power frontier is controlling beam loss to minimize residual activation

1 nA protons at 1 GeV, a 1 Watt beam, activates stainless steel to 80 mrem/hr at 1 ft after 4 hrs



Courtesy J. Wei

SNS Linear Accelerator



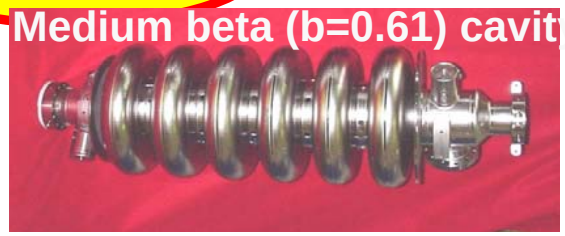
- World's first high-energy superconducting linac for protons
- 81 independently-powered 805 MHz SC cavities, in 23 cryomodules
- Space is reserved for additional cryomodules to give 1.3 GeV

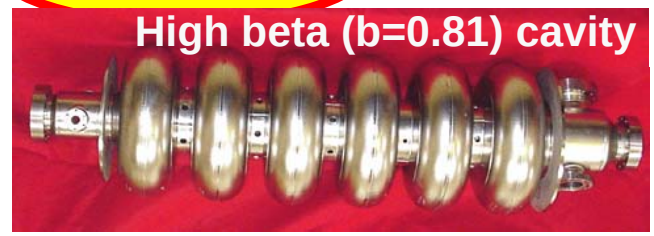
Courtesy Stuart Henderson, then Director of Accelerators SNS

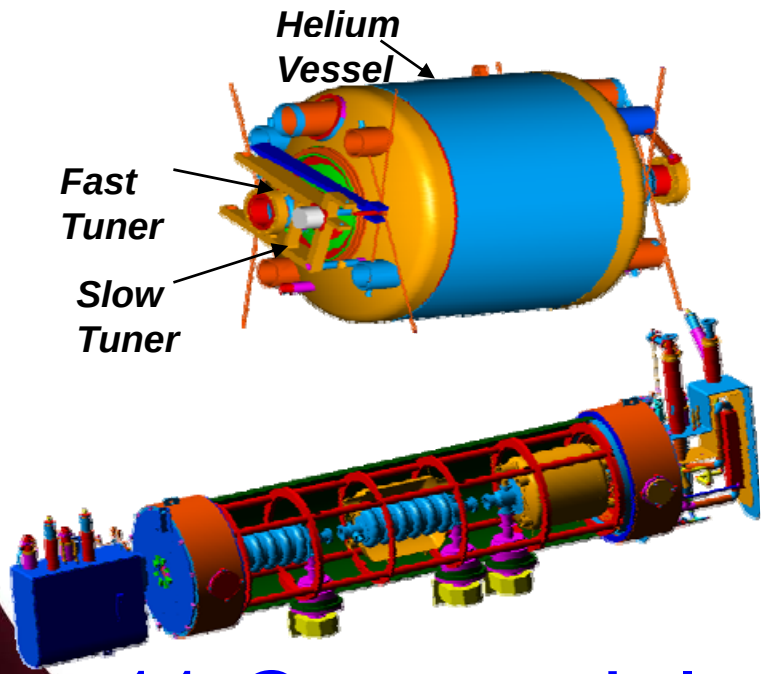
SNS Cavities and Cryomodules

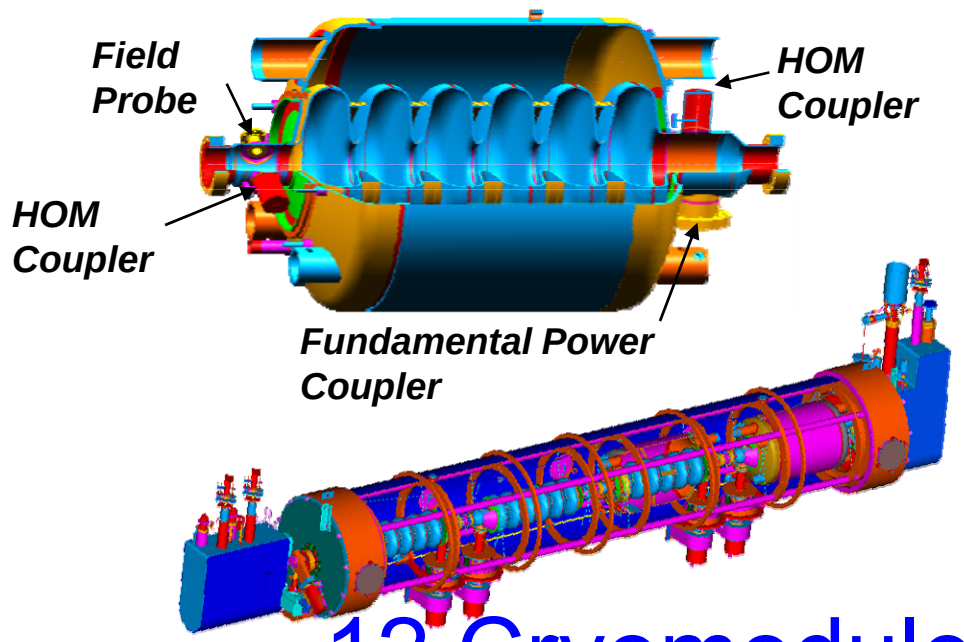
β=0.61 Specifications:
E_a=10.1 MV/m, Q_o> 5E9 at 2.1 K

β=0.81 Specifications:
E_a=15.8 MV/m, Q_o> 5E9 at 2.1 K







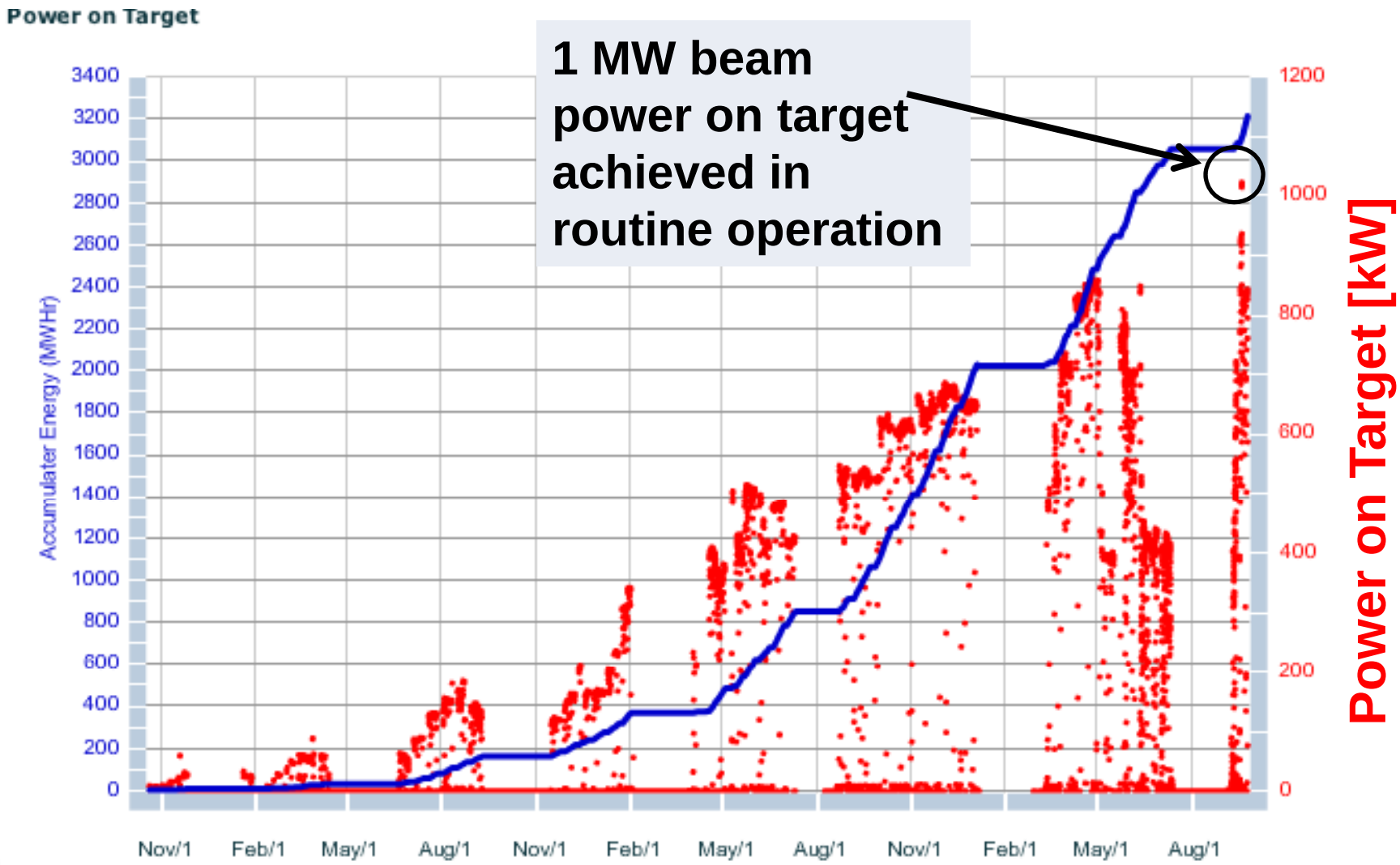


11 Cryomodules

12 Cryomodules

Low Beta cavities have lower gradient

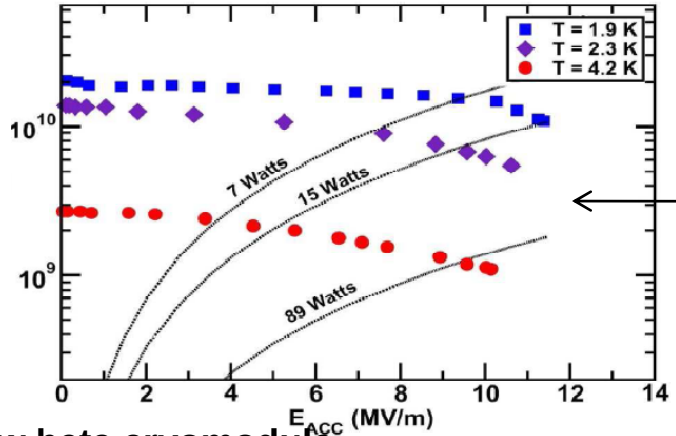
SNS Beam Power Performance History



Courtesy Stuart Henderson

Superconducting Low Beta Structures

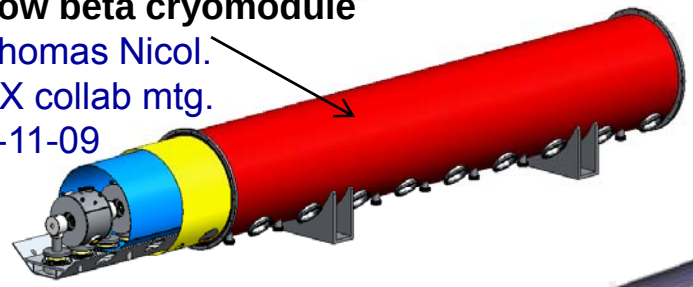
SSR1



ANL TSR

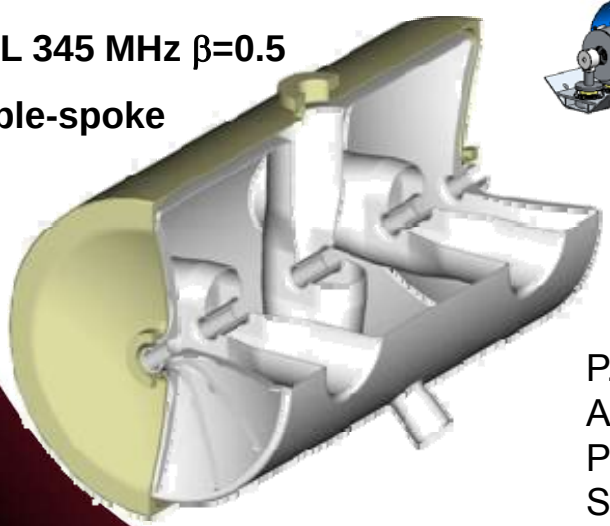
Low beta cryomodule

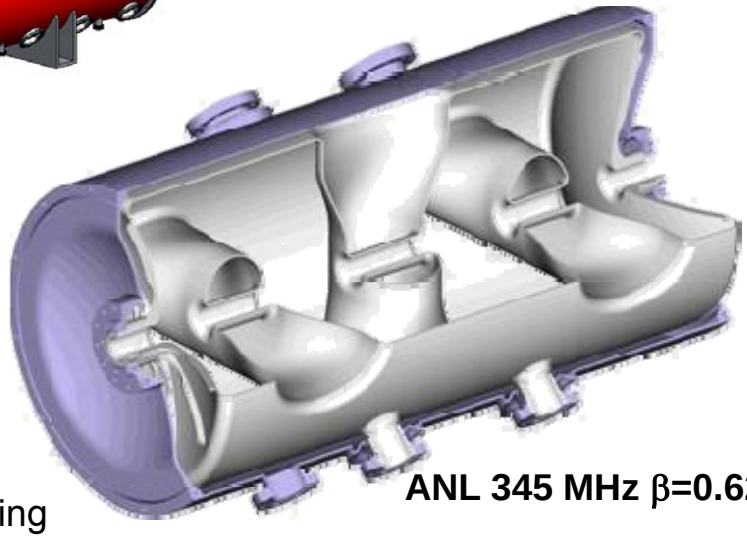
Thomas Nicol.
PX collab mtg.
9-11-09



ANL 345 MHz β=0.5

Triple-spoke





ANL 345 MHz β=0.62

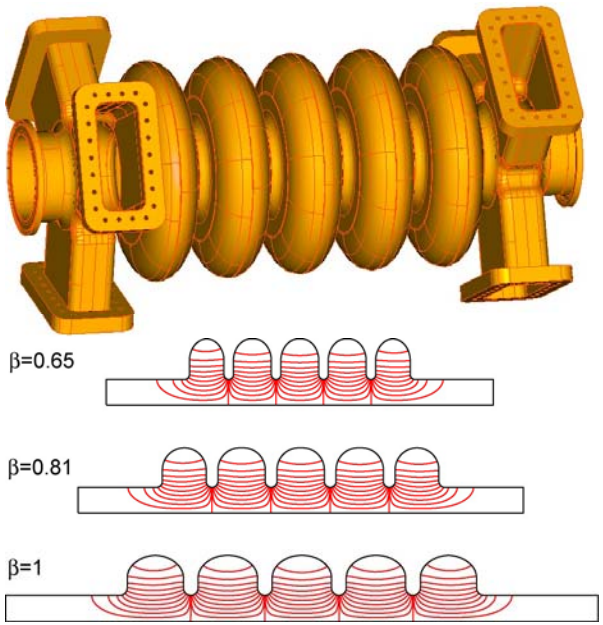
Triple-spoke

P.N. Ostroumov
ANL Physics Division
Project X collaboration meeting
September 11, 2009

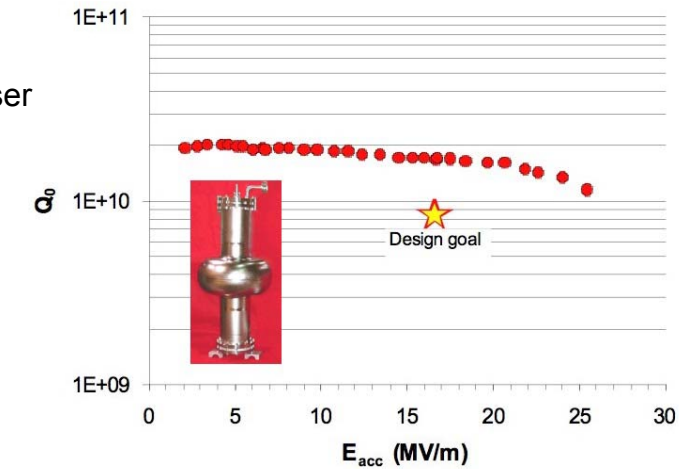
Jefferson Lab

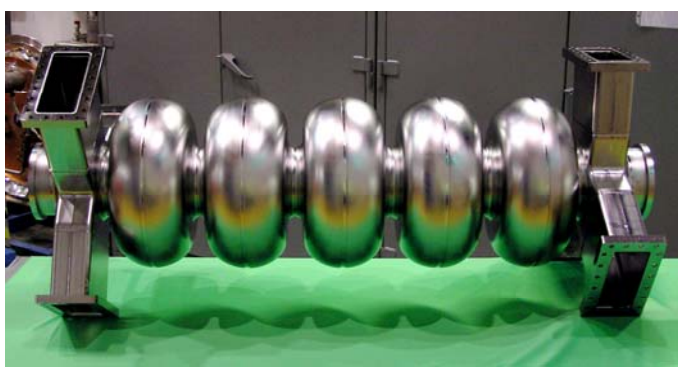
JLab High-Current Cavity

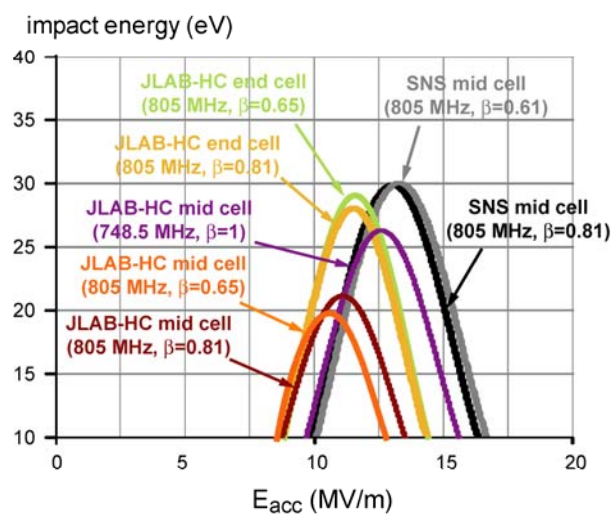
- Development of electron cavity for ≥100 mA



F. Marhauser
PAC09

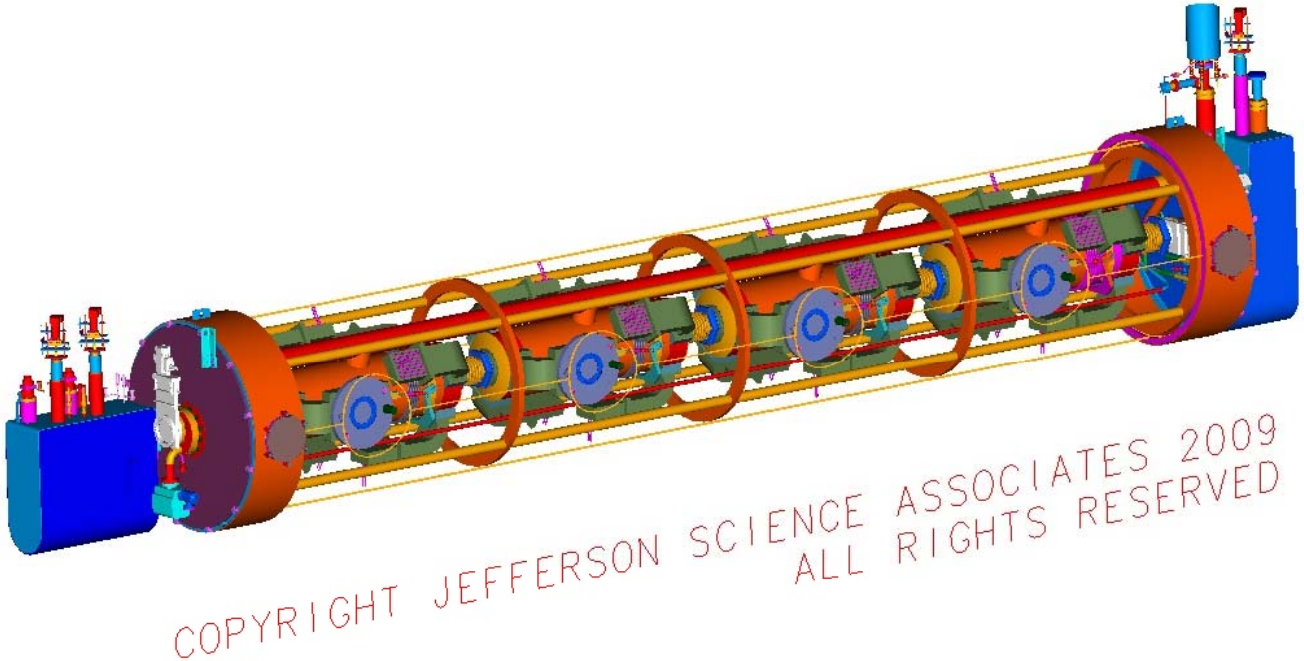






JLab High Current Cryomodule

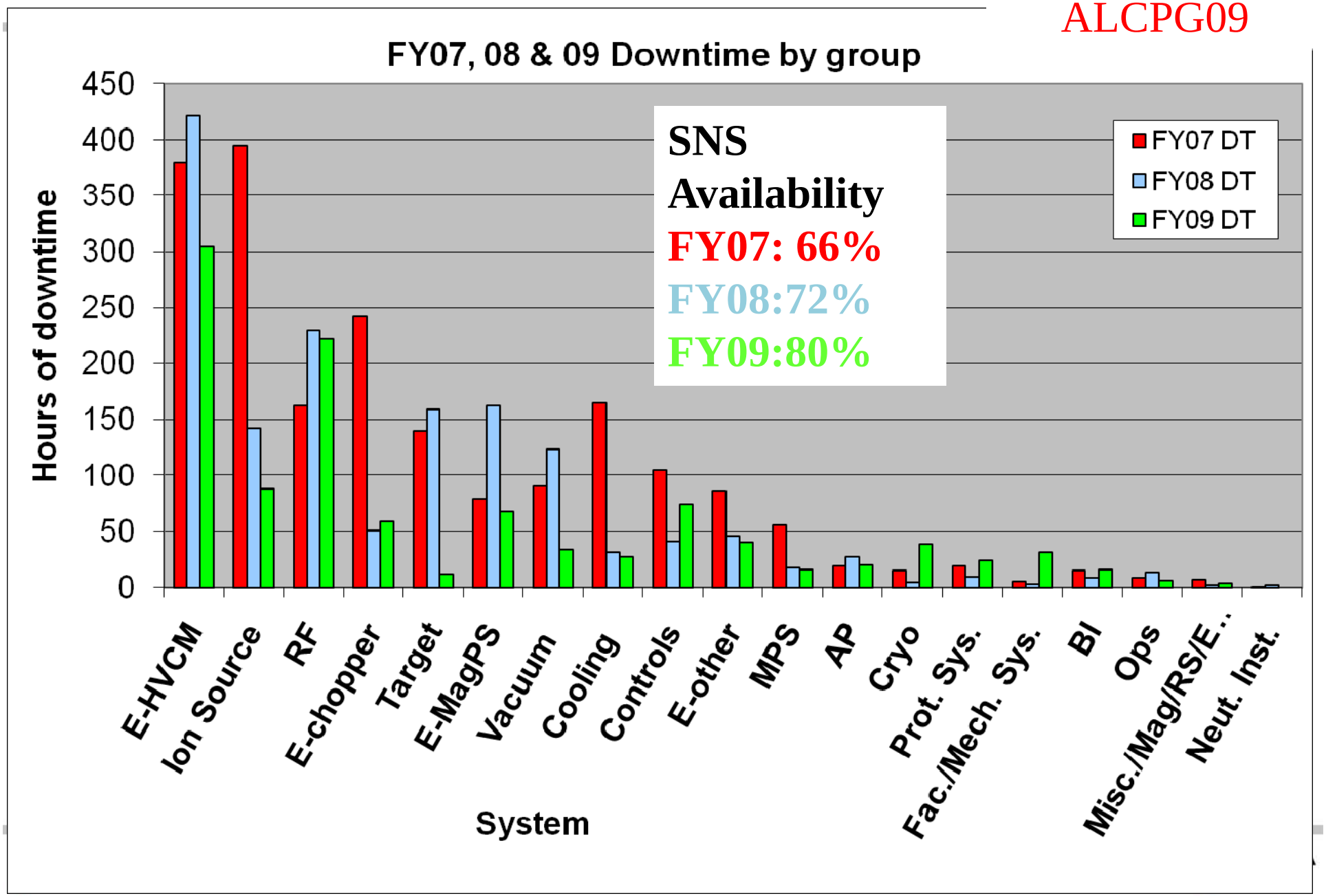
- JLab 700 MHz ERL module (based on modified SNS layout)
- Could be economical if it can operate in BCS dominated regime
- Very large apertures (halo!)
- Very high BBU threshold
- Use TV band RF sources



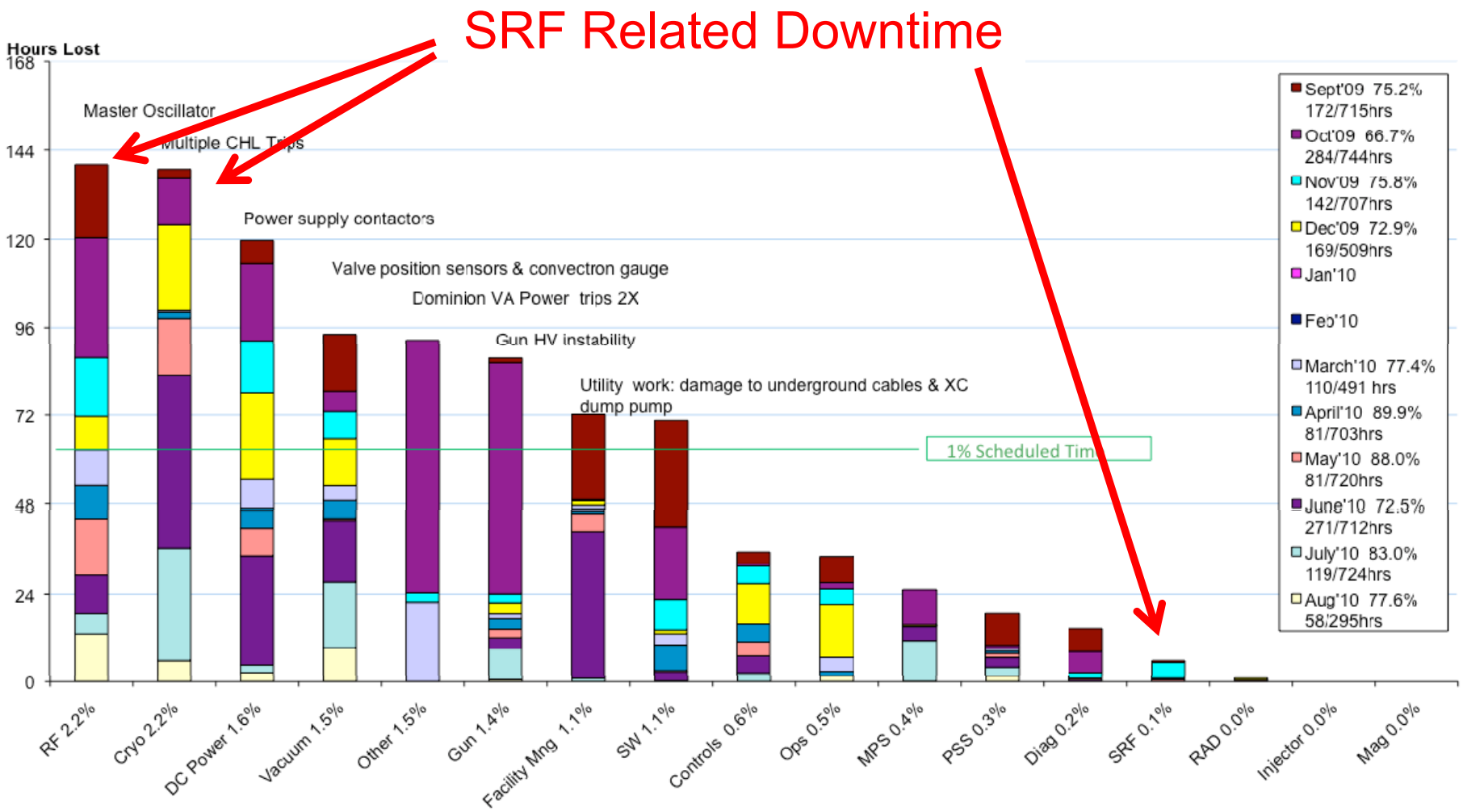
Availability Data

SNS Downtime by System

Stuart Henderson
ALCPG09



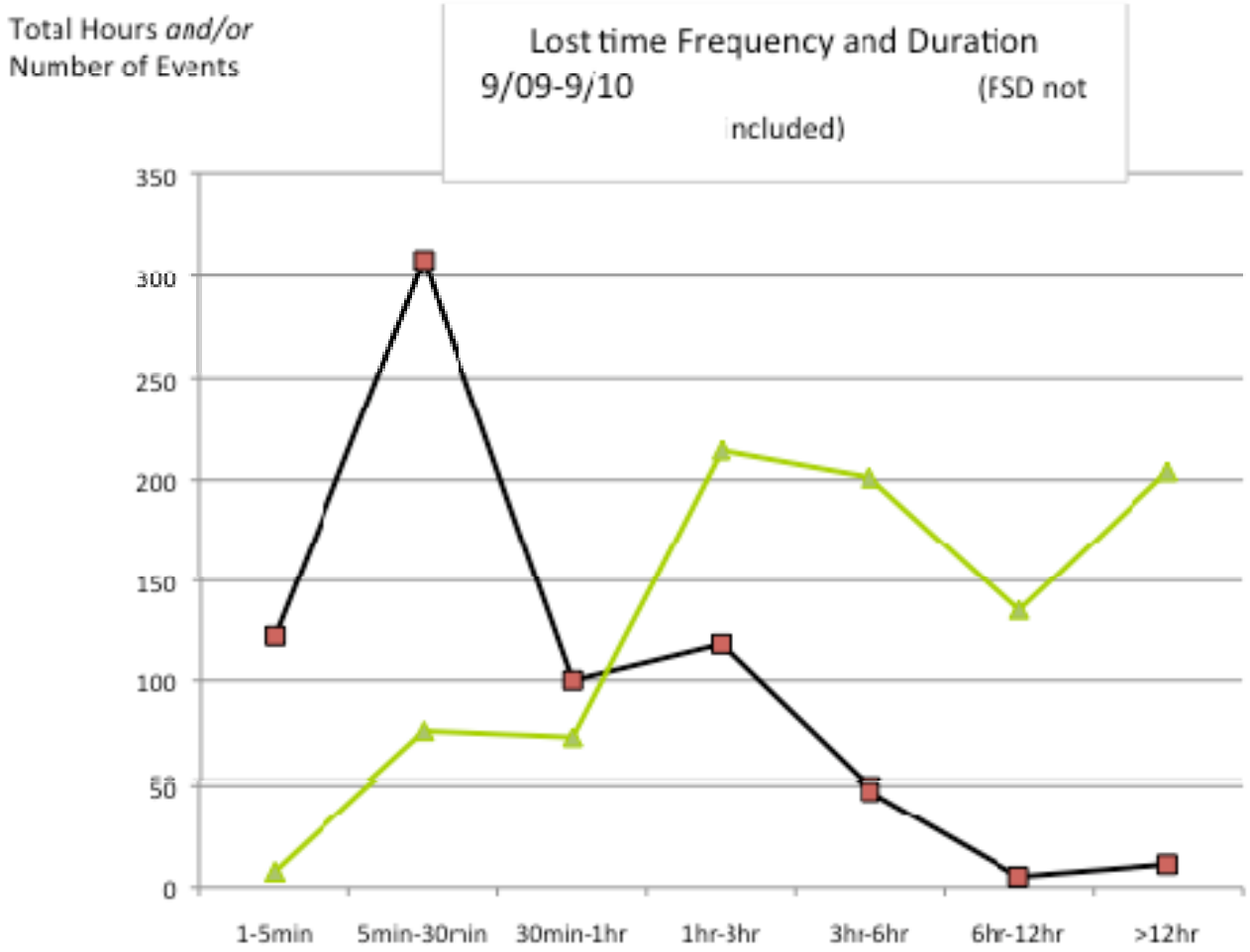
CEBAF Downtime from All Sources



RF Downtime

- RF outages can last up to more than 12 hours
- The data for CEBAF for the 12 months August 2009 to September 2010 showed 711 events totaling 909 hours

CEBAF RF Downtime Data

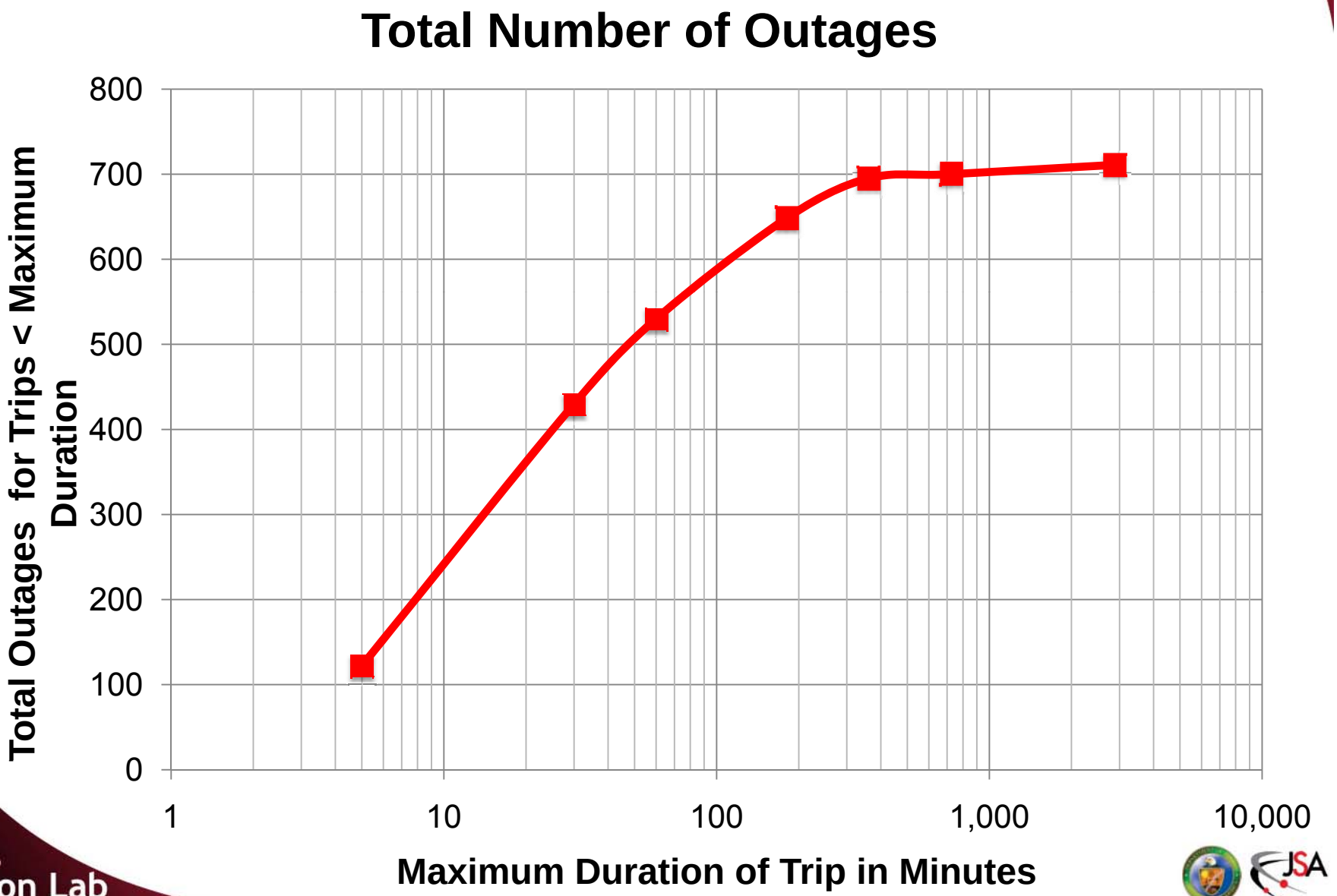


Time	Number	Total Time
1-5min	122	7.52
5min-30min	308	74.88
30min-1hr	100	71.73
1hr-3hr	118	214.40
3hr-6hr	47	201.10
6hr-12hr	5	135.10
>12hr	11	204.13

RF Downtime

- RF outages can last up to more than 12 hours
- The data for CEBAF for the 12 months August 2009 to September 2010 showed 711 events totaling 909 hours
- My preferred way of showing the data is to plot the number of outages less than a maximum duration against the logarithm of the maximum duration
  - In general, this plot is quasi-linear and unique
  - Plotting histograms of the data depends on the relative size of the bins and is not unambiguous

CEBAF RF Availability Data for 12 months



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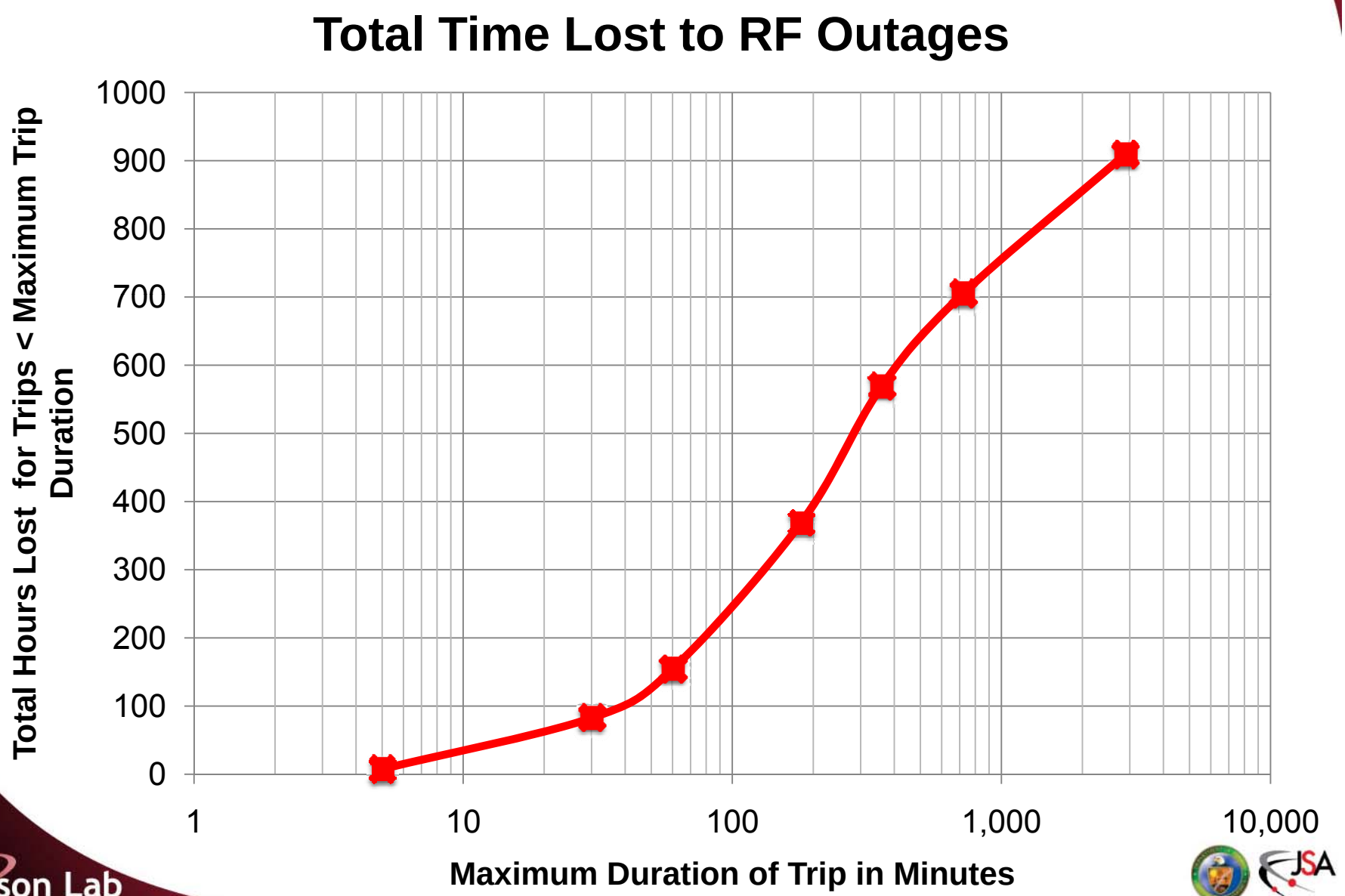
CEBAF RF Availability Data for 12 months



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CEBAF RF Trip Data

- CEBAF RF cavities are pushed to their absolute limits to meet the Physics needs of the Users
- Maximum acceptable trip rate for our Users is 15 trips/shift
  - Each trip is reset in ~45 seconds
- RF Trips are due to arcing on the waveguide window
  - Fast trip on photodiode looking at window
  - Slow trip on vacuum pressure
  - "TrueArc" is when both occur simultaneously
    - We have many other trips
      - But are they actually false trips?

Good News and Bad News

- The arc trips are believed to be caused by the ceramic or polyethylene window charging up due to field emitted electrons
  - We have modified our recent cryomodules to put a “dog-leg” in the waveguide between the cavity and the window
    - Prevents line-of-sight from cavity to window

Good News and Bad News

- The arc trips are believed to be caused by the ceramic or polyethylene window charging up due to field emitted electrons
  - We have modified our recent cryomodules to put a "dog-leg" in the waveguide between the cavity and the window
    - Prevents line-of-sight from cavity to window
    - **Reduces "TrueArc" faults by a factor of 9**
- However, other trips now dominate
  - The average "TrueArc" trip rate for the modified cavities is 32/cryomodule/year
  - **The total number of arc trips in one calendar year is 24,000**

C-50 Trip Data

- TrueArcs are now <5% of the total number of Arcs
- Enormous variability between different cryomodules
- All Arcs are strongly dependent on the accelerating gradient
  - Nearly all are caused by field emission

C50's	Total Fault Ct	TrueArc
1L04	999	49
1L05	379	21
1L06	1010	81
1L11	620	40
2L04	789	28
2L07	322	17
2L09	468	4
2L15		
2L16	831	18
Total	5418	258
Avg	677	32
Std Dev.	271	24

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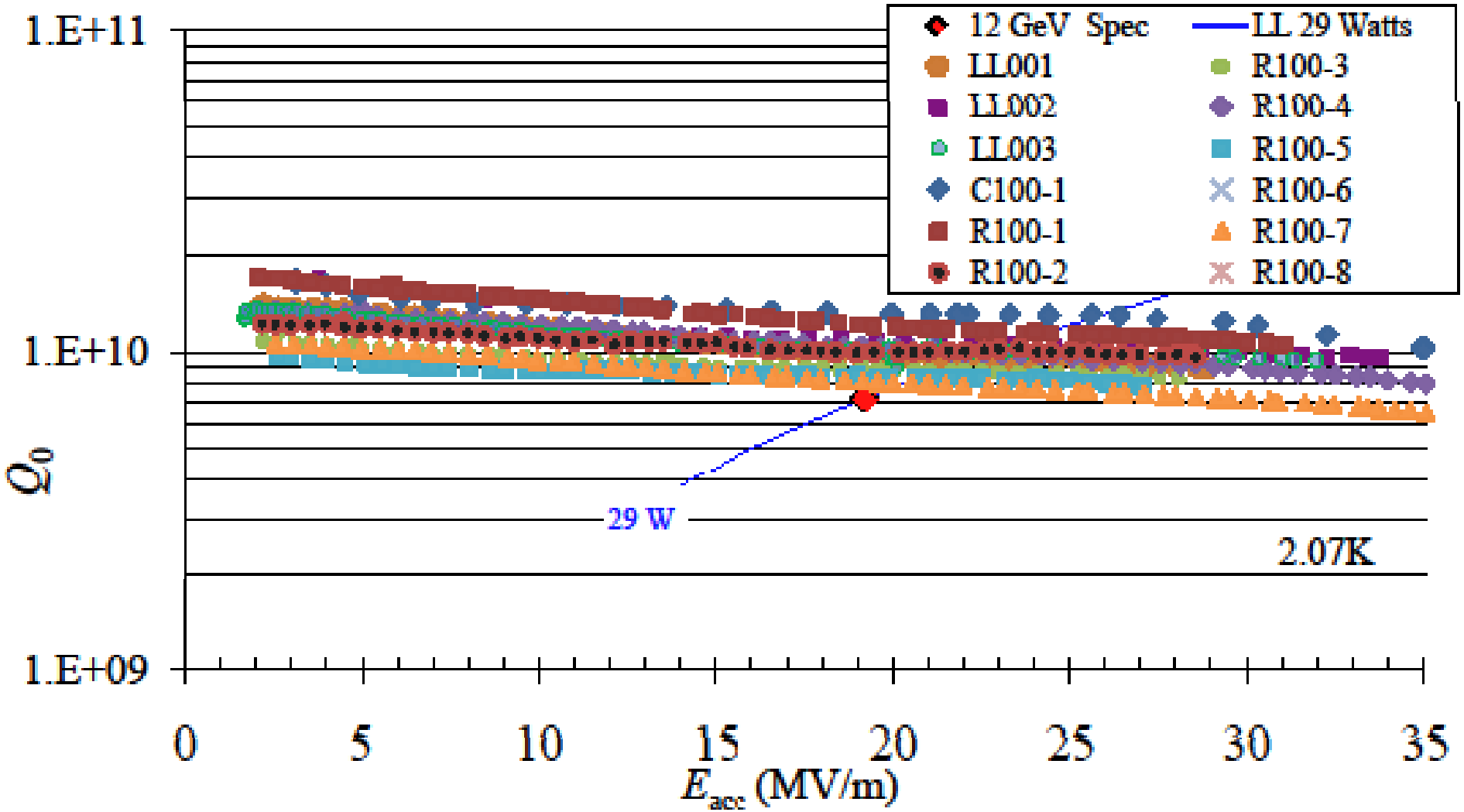
Electropolished Prototype Upgrade Cavity Performance



Trip Rate and Availability Units

- An ADS machine would function ~44 weeks a year
  - Means that there are two 4-week shut-downs per year
  - 44 x 168 hours = 7392 hours
- For a one GeV accelerator there will be 12-15 cryomodules
  - CEBAF 12 GeV Upgrade is 10 cryomodules (8 cavities) for 1 GeV
  - SNS is 23 cryomodules (3 or 4 cavities) for 800 MeV
- I propose that we normalize the trip rate and availability data to

1,000,000 cavity-hours per year

  - It's a round number and about the right order of magnitude

The **CLEAN** Proposal

CW
Linac for
Efficiency and
Availability
i**N**novation

CLEAN proposal

- CLEAN (a CW Linac for Efficiency and Availability iNnovation) is a proposal to demonstrate a high-efficiency, high-reliability superconducting linac section at Jefferson Lab to serve as a model for future SRF linacs
- The goal is to improve the reliability (downtime) by a factor of five and to reduce the energy consumption by a factor of two compared to the present CEBAF sections
- The outcome of this project will increase the energy efficiency of future accelerators, reduce the carbon footprint, and make it more environmentally acceptable to propose these large installations.

Phases of CLEAN

Phase 1a – Evaluation and design

- Detailed downtime records have been kept since CEBAF was first commissioned
- We will use these data to develop a detailed reliability model at the component level for every aspect that touches the reliability and the energy efficiency of the linac, including the RF plant, the superconducting cryomodules, cryogenics, protection systems, etc.

Phase 1b – Automated fault recovery

- In parallel with evaluation and design, we will develop sophisticated, fully automated fault recovery systems using CEBAF as a test-bed
    - CEBAF has had a semi-automated fault recovery system for many years and this would serve as the basis for the fully automated system

Automated Fault Recovery

- The CEBAF semi-automated fault recovery system is based on:
  - Fault detection
  - Removal of RF power from the affected cavity
  - Interruption of beam delivery to avoid maintaining an existing cavity waveguide arc with beam-driven RF
  - Restoring RF power
- All of these steps are currently automated but, at present, the final step of restoring beam is done manually
- We will develop redundant levels of security to enable reliable, automated restoration of the beam

Replacing RF Gradient

- When a cavity or an RF system has to be taken off-line
  - The gradient is redistributed
  - The focusing is recalculated and established for the new gradient profile
- These steps are done automatically but they are not yet part of an integrated fault recovery system
- We expect to demonstrate the operational functionality of a fully automated recovery system
- For a proton accelerator, the cavities would also have to be re-phased
  - This will not be tested at CEBAF

Phases of CLEAN

Phase 2 – Procurement and installation

- Procure and install upgraded components in five zones of the present CEBAF accelerator
- Involves a complete overhaul of the RF plants, including upgrade of the RF controls to a newer digital system developed for the 12 GeV Project

Phase 3 – Operation and assessment

- The five zones will be monitored during routine accelerator operations and their reliability and efficiency compared to the model and to the other, unimproved, zones
    - This is a real-life test of a high-reliability, high-efficiency linac section with sufficient statistics to be able to draw conclusions for future projects

Conclusions

- Large scale CW SRF is viable for proton drivers
- Prototype cavities exist for all beta ranges
- No show stoppers to running CW
- Robust high-power couplers must be used
- Main challenges may be halo / beam loss / trip rate
- Q_o (residual resistance) is significant cost driver
- Reliability and Availability need focused attention
  - JLab has presented a proposal to study and improve the present state-of-the-art

Need a small, accelerator-driven subcritical reactor test facility to demonstrate feasibility