SRF Cavity Vertical Test Infrastructure at Fermilab, and Highlights of the ILC Cavity R&D Program

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Outline

Vertical Cavity Test Facility (VCTF)
- Requirements
- Sub-system designs
- Fabrication, assembly, and integration
- Operation
- Upgrades

ILC Cavity R&D Program
- Cavity processing facility commissioning
- Quench origin localization/identification
  - Fast Thermometry, Second Sound, Optical Inspection
- Defect repair, alternate processes
  - Grinding, Laser Re-melting, Tumbling (CBP), Dressed Cavity EP
- Medium-Field Q-slope studies
Background

Fermilab decided ~2005 to embark upon a substantial program of developing infrastructure and staff to allow them to become a significant contributor and participant in the field of SRF, especially with regards to the ILC.

Required facilities were identified:

- Cavity inspection/measurement/tuning
- Cavity processing/assembly
- Cavity vertical test
- Cavity string assembly
- Cavity horizontal test
- Cryomodule assembly
- Cryomodule test
Vertical Cavity Test Facility (VCTF)

One of the first facilities to be undertaken.

Project inception: December 2005

Initial requirements:

- Test bare 1.3 GHz single-cell and 9-cell cavities
- RF power up to 250W
- Measure $Q_0$ vs $E$, $Q_0$ vs $T$, radiation (FE)
- Maintain “controlled area” in building (radiation shielding)
- Use existing cryoplant (1500W 4K refrigerator, 250L/h liquefaction, 125W pumping capacity, He recovery & purification)
VCTF Design Tasks

- Civil Construction
- Cryostat
- Radiation Shielding
- RF System (LLRF, HPRF, controls) and DAQ
- Interlocks/Personnel Safety Systems
- Cryogenic Controls
- Insert (cavity support)
- Ancillary Systems (staging area, 120°C bake)
VCTF Design: Civil Construction

An almost “green field” site – Magnet Test Facility building, w/existing cryoplant, superconducting and conventional magnet test stands – no SRF-specific infrastructure.

Requirements:

- Crane hook height limitations
  - Provide a pit/hole for cryostat installation
- Trenching for cryo services and instrumentation access
- Guard rails/fencing for personnel safety
- Minimize disruption of existing operations
2’ concrete walls in pit. Pit is 2’ 8” below grade, 7’4” x 8’4” in area.

1’ thick concrete “tube” for cryostat.

Fiberglass liner, 20’ long.
VCTF Design: Civil Construction

At construction start – June 22, 2006
VCTF Design: Civil Construction

During construction – early July, 2006
VCTF Design : Civil Construction

Shaft complete – July 5, 2006
VCTF Design : Civil Construction

Construction complete (pit, trench, covers, fencing) – August 2, 2006. Major construction work ~2 weeks.
VCTF Design: Cryostat

Requirements:

- Bath temperature: 1.5-4.5K
- Bath pressure: 3.5 – 1000 Torr
- He supply rate: > 9 g/s
- Meets ASME BPV Code (Fermilab ESHM 5031 applies)
- MAWP: 65 psig
- Internal heater (LHe boiloff): 250W
- Static heat load: ≤ 6W
- Deep enough for 2 9-cell ILC cavities
- Ambient magnetic field: ≤10mG
VCTF Design : Cryostat

Specifications :

- Vacuum vessel 18’ deep, 42” ID
- He vessel 16’ deep, 26” ID (usable aperture)
  Fits 2 9-cell ILC cavities (spaced vertically)
- 1500L LHe capacity
- Warm (300K) & Cold (2K) magnetic shields
- Internal heater (250W, wire-wound non-inductive)
- Cernox® RTD’s to monitor bath temperature
- AMI LHe level probes (2, 80” each, 30” overlap)
- Pressure transducers (0-100 & 0-1000 Torr ranges)
- 80K thermal shields
- Bottom and top fill valves for He filling & topoff
VCTF Design: Cryostat

- Vacuum vessel
- Phase separator
- Helium vessel
- Thermal (80K) shield
- HX/pumping line
- Fill valve actuators
- Vacuum vessel
VCTF Design : Cryostat

Procurement contract awarded September 2006

(PHPK Technologies)
VCTF Design: Cryostat
Received at FNAL February 2007
VCTF Design: Cryostat

Installed March 2007
VCTF Design: Radiation Shielding

Requirements:

- Attenuate radiation from field emission in order to
  - Maintain < 5 mR/hr outside shielding
  - Maintain < 0.25 mR/hr in normal working areas (“Controlled Area”)
- Accommodate e- energies ~ 50 MeV
- Accommodate two-cavity operation (one at a time)
- Easily moved over pit
- Balance cost/size/manufacturability
VCTF Design : Radiation Shielding

Modeling :

MARS15 used to model radiation field from cavity
  - Including appropriate neutron production cross-sections
  - 2 models used
    - monoenergetic & unidirectional e- beam
    - spatially dependent e- energy and angular distribution
    - up to 50 MeV maximum e- energy

Full 3-D geometry applied
  - trench
  - pit
  - shielding block
  - internal shielding (Pb, SS, borated poly)
VCTF Design: Radiation Shielding

Shielding block - concrete (top) and steel (bottom)
Borated poly (n absorber)
Concrete walls of shaft, pit, and trench

Stainless steel
Pb
ILC-style 9-cell cavity
VCTF Design : Radiation Shielding

Maximum dose rate (localized over ~ 5cm area) = 1.6mR/hr (50MeV, realistic model)

Efficacy of basic parameters of shielding system verified by modeling to be acceptable; detailed design work follows.
VCTF Design: Radiation Shielding

Specifications:

- Composite movable shielding block
  - 6” thick steel base plate, ~31,000lbs
  - 18” high concrete blocks, ~32,000lbs
- Chain drive, 3 HP motor/transmission mounted on block
- Hardened steel rollers & rails
- Motor control unit on block
VCTF Design: Radiation Shielding

- Concrete blocks
- Drive chains
- Steel baseplate
- Hardened steel rails
- Mast for power & signal cables
- Motor and gear drive
VCTF Design : Radiation Shielding

Shielding lid assembly – ~1 month from delivery of components
VCTF Design : RF & DAQ System

Requirements :

• Provide stable RF power to the cavity, with control of amplitude, relative phase, and frequency
• Measure CW incident, reflected, and transmitted power of the cavity (including transmitted power from HOM couplers if so equipped)
• Measure radiation ($\gamma$) produced from FE (field emission) or MP (multipacting)
• Measure cavity frequency, and test condition variables
• Provide interlocks for personnel
• Provide automated data acquisition and control (reproducibility)
• Calculate cavity performance parameters ($E$, $Q_0$) from power measurements and field decay time constant
VCTF Design: RF & DAQ System

Specifications-1:

- **Frequency:**
  - Manually adjustable (coarse & fine tuning) over the range 1.25-1.35 GHz
  - Measure and record frequency as part of DAQ SW
  - Resolution/sensitivity/stability: < 1Hz

- **Phase:**
  - Manual phase control
  - Programmable phase control, range: 360°, resolution ~ 0.1°
  - Automatic phase optimization routine in SW
  - Phase stability: ~1° drift over ~10 minutes
VCTF Design : RF & DAQ System

Specifications-2 :

• Radiation / Interlocks :
  ▪ Measurement and logging of radiation inside Dewar shield enclosure by DAQ system.
  ▪ High power RF enable interlocked w/ Personnel Safety System.
  ▪ Interlock system monitors both external-to-Dewar area monitor radiation signals and Dewar lid closure status, and displays status.
VCTF Design : RF & DAQ System

Specifications-3 :

• Power Supply & Measurement :
  ▪ RF Power supplied via 500W SS amplifier, 1270-1310MHz, 50dB gain min.
  ▪ Amplifier protected against maximum reflected power
  ▪ Measurement of $P_i$, $P_t$, $P_r$, and $P_{HomA,B}$ using calibrated power meters, and also with crystal (diode) detectors (for time dependent measurements or qualitative visual observation)
  ▪ Variable attenuator (~ 30dB) in series w/ switchable 30dB gain amplifier to regulate $P_t$ input signal on crystal (diode) detector, to maintain operation in the square-law regime, and regulate loop gain (prevent oscillations)
  ▪ RF system stable and operable between $E = 0.1 – 45$ MV/m
  ▪ RF Pulse capability – pulse width ~ 100ms – 5 sec, at rep rates up to 10Hz
  ▪ Computer controlled amplitude and phase adjustment via VM (vector modulator) amplitude resolution < 0.2 dB, phase resolution < 0.5°
Specifications-4:

• Acquisition and Control SW:
  ▪ Automatic $P_t$ decay measurement
  ▪ Automatic calculation of $\beta$
  ▪ Interactive cable calibration routine
  ▪ Continuous online display of $E$, $Q_0$, Rad, freq, $P_i$, and $P_r$
  ▪ Online display of $P_i$, $P_r$, $P_t$, and correction (calibration) factors
  ▪ RF output power control
  ▪ Phase control
  ▪ Phase optimization routine
  ▪ Display of cryogenic status (temps, Dewar pressure(s))
  ▪ On-demand calculation of $Q_0$, $Q_{FP}$, $Q_{FPC}$, $Q_{ext \: HOM1}$, $Q_{ext \: HOM2}$, $E_{acc}$ and all associated errors.
  ▪ Logging of all data to ASCII (tab-delimited) file
  ▪ Graphic display of $Q_0$ vs $E_{acc}$
  ▪ Graphic display of Rad vs time, w/ Rad vs $E_{acc}$ option
VCTF Design : RF & DAQ System

Design approach was to adopt the JLab production-style RF/DAQ/Control system. This was done in order to:

- Minimize development costs
- Minimize risk
- Maximize ease of operation
- Robust system for use in a production, not development, facility, usable by non-experts
- Tight schedule requirements

We would modify as needed to accommodate:

- Frequency change (1500/805 → 1300 MHz)
- Newer (or obsolete) components
VCTF Design: RF & DAQ System

LLRF System
VCTF Design: RF & DAQ System

HPRF System
VCTF Design: RF & DAQ System

- PSS/Interlocks
- RF/DAQ
- RF/DAQ
- Cryo

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VCTF Design: RF & DAQ System

- LV power supplies
- Power msmt module
- Power Meters & Freq. Ctr.
- RF source
- RF status
- Dewar htr PS
- Dewar pressure
- Cavity Temp
- Rad det. readout
- Transmitted power module
- RF source control (VM) module
- Signal conditioning module
VCTF Design: RF & DAQ System

Overview of DAQ pgm.
VCTF Design: RF & DAQ System

Menu-driven, semi-automated cable calibration routine. Full cable calibration required for every test.
VCTF Design : RF & DAQ System

Automated decay measurement for field probe calibration.
VCTF Design : Interlocks

Requirements :

- Protect personnel form exposure to hazards – ionizing radiation
- Provide redundancy
- Support flexible operational modes
- Independent from RF/DAQ system
  - (physically and operationally)
- Expandable (additional test stands)

Approach : Disable RF operation if

- Shielding lid is moved from position
- External radiation monitors detect signal > bkgrd (lid closed)
- Internal (in-pit) radiation monitor detects signal > bkgrd, (lid open)
VCTF Design : Interlocks

Specifications :

- Magnetic and mechanical switches on shielding lid
  - Lid in position for RF permit
  - Redundancy, independence
- AC contactor to disable AC supply to high power amplifier
- Narda RF switch disables LLRF output from VM
- Narda RF Relay disables input to amplifier
- DC Contactor disables DC supply to low power amplifier
- Key switch required to “arm” system
  - Same key used to enable shielding lid motion control
- Standard Fermilab RadCon Area Radiation Monitors
  - 3 on shielding lid, 1 in pit
  - Remote monitoring/data logging by RadCon
- All faults latch
VCTF Design: Interlocks

- Status indicators
- Expansion capability
- Key switch – system reset
- Key switch enable – for 3 Dewars
- Area Radiation Monitors – remote readout & data logging
VCTF Design : Cryogenic Controls

Requirements :

• Provide an LHe bath capable of operation between 4.3 and ≤ 1.6K

• Fast cooldown rate - minimizes Q–disease susceptibility

• Instrumentation to provide readout of Dewar pressure, temperature, and LHe level

• Fast turnaround –
  ▪ Cooldown & fill : 4-6 hours
  ▪ Pumpdown : 2-4 hours (can be concurrent w/ fill if not performing $Q_0$ vs $T$ measurements above 2K)
  ▪ Remnant LHe boil off : 3-4 hours (200-250W for 800L)
  ▪ Warm up to 300K : 15-17 hours (350 K He gas at ~2g/s)

• Integration with existing cryoplant & controls

• Path for automation
VCTF Design: Cryogenic Controls

Existing Resources/Facilities

- **1500W LHe refrigerator**
  - Liquefaction capacity of ~250L/hr (design > 300L/hr)
  - LHe transfer rate up to 25 g/s
  - 10,000 L LHe storage capacity
  - 10,000 Gal LN$_2$ supply
  - Existing transfer line to magnet test stand adjacent to VTS site

- **Pumping System**
  - 2 Kinney pumps, 4 and 2 g/s capacities, 6 g/sec total (125W)

- **Recovery/Purification System**
  - Recovery compressors, 20 g/sec
  - Partial purification system (5-10%)
  - “Arc Cells” for contamination monitoring
VCTF Design : Cryogenic Controls

Specifications/Design :

• Siemen’s PLC (Simatic 545) used as interface to field instrumentation
• PLC logic is configured to establish ‘permits’ and ‘interlocks’
• iFix (commercial controls SW) used for HMI/SCADA; already in use for cryo system operation
• Use iFix “Recipe” programming to automate the cryogenic sequences (fill, pumpdown, warmup, etc.)
• System is scalable
VCTF Design: Cryogenic Controls

He return control valves

LHe bath temps

Pumpdown valve control (supports automatic mode)

Top LHe fill valve control

Bottom LHe fill valve control
VCTF Design : Dewar Insert

Requirements :

- Support up to 2 ILC-design 9-cell cavities
- Provide active pumping (cavity vacuum) capability
  - Rouging pump connection
  - Turbopump & controller
  - RGA
  - Valves
  - Vacuum gauges
  - Purge line (clean N₂ gas)
- Provide numerous feed-thrus for RF signals, diagnostics, etc.
- Incorporate radiation shielding
- Minimize thermal load (thermal radiation baffles)
VCTF Design : Dewar Insert

Design features :

- Vacuum isolation valves
- Thermal rad. baffles
- Rad shielding (poly)
- Rad Shielding (steel)
- Rad Shielding (Pb)
- Pumping line
- 9-cell cavity in support cage (2 shown)
- Scroll Pump
- Turbopump
- Vacuum gauge
- RGA
- Feed-thrus for RF, instrumentation

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VCTF Design: Dewar Insert

- RGA
- Vacuum gauges
- Vacuum isolation valves
- Turbopump
- Feed-thrus for RF, instrumentation
A “staging area” is used to store the inserts, and provide an appropriate environment for mounting and instrumenting a cavity before test.

The bottom section is outfitted with 4 HEPA filters (2 ea. side) and can be screened off to create a “reasonably” clean-room (Class 100-1000?).

There is an “anteroom” between the two sides, to provide a gowning area and to house the particle counter and supplies.
VCTF Design: Staging Area

- Plastic walls and “ceiling”
- Cavity vacuum gauge readout
- HEPA FFU’s
- Clean Room flooring tiles
- Strip curtain between anteroom
- Particle counter
VCTF Design : Cavity Bakeout

Requirements:

- Provide a system to bake 9-cell ILC cavities at a temperature of 120°C for 48hrs
- Cavity is to be actively pumped (maintain vacuum) during bakeout
- System should be easy to implement
- System should be compatible with existing inserts (cavities to be baked in–situ on the test stand)
- Temperature control should be automatic
- Adaptable for 9-cell or single-cell cavities
VCTF Design : Cavity Bakeout

Specifications/Design :

- Commercially available baking blankets (HTS/Amptek)
- Fiberglass insulation, silicone-coated fiberglass cloth exterior
- Designed to accommodate cavity in cage, mounted onto insert, attached to pumping line
- 4 segments, 7 heater zones, each w/ control and limit TC’s
- Maximum heater (zone) output 2.2 W/in$^2$, (360W total per zone)
- Each zone independently controlled
VCTF Design: Cavity Bakeout

All 4 segments mounted on cavity

One of 4 segments

Two heater zones per segment (except bottom segment)

Heater controller
VCTF Timeline

- Project Start – Dec 2005
- Civil Construction – June/July 2006
- Cryostat proc/fab – Sep 2006/Feb 2007
- Cryosystem mod/integration – Oct 2006/Apr 2007
- RF/DAQ system fab/test – Sep 2006/Apr 2007
- Cryostat installation – March/April 2007
- Cryostat cold commissioning – May 2007
- RF system commissioned (low power) – June 2007
- Radiation shielding complete – July 2007
- First single cell test – July 24, 2007
- First nine-cell test – September 9, 2007
VCTF Operations

Initial operations aimed at system commissioning

Single cell test
- Cavity processed and prepared at JLab
- Had He leak during low power test, so re-evacuated
- Inner magnetic shielding not in place yet (so expect lower $Q_0$ values)
- System worked!

Essentially duplicated performance measured at JLab!

![Graph showing Q vs Gradient]

**ILC-SC01 - Q vs Gradient**
Tested 07/24/07

- Multipacting
- Initial Field
- Emission
- Ultimate Performance
VCTF Operations

Initial operations aimed at system commissioning

Nine cell test

- Cavity processed and prepared at JLab
- Inner magnetic shield in place now
- Cavity evacuated at JLab, not actively pumped

Once again, duplicated performance (quench limit) measured at JLab. We consider the VTS functional!
VCTF Operations

We then commission other systems…

Active cavity pumping

- Vacuum system cleaned, assembled, and tested
- Cavity processed at JLab, sent to FNAL under vacuum
- Hooked up to pumping line, tested before/after valve opened

No effect (additional FE) seen when cavity actively pumped. Pumping line is clean (but not so the cavity!).
We then commission other systems…

Variable coupler

- Previously tested cavity, limited by quench (20 MV/m), had FE
- Variable coupler installed in cleanroom, cavity evacuated

No effect (additional FE) seen when coupler operated. However increased FE probably introduced when coupler assembled to cavity.
VCTF Operations

Once commissioned, a steady increase in test throughput, reaching an average of about 6-7 tests/month.
VCTF Upgrades

Average test rate of 6-7 tests/month (maximum of 10), or 75-90 tests/year, insufficient for FNAL long-term needs.

VCTF to be upgraded to increase testing capability, for a maximum test rate of ~200 tests/year.

- Two additional (larger) cryostats
- Additional 2K pumping capacity
- Multiplex RF system
- Permanent (larger) staging area
- Increased He gas storage and improved liquefaction
- Increased He recovery and purification system capacity
VCTF Upgrades

Cryostats

- Additional shafts/pits/trenches excavated and constructed.
- Two additional cryostats (larger diameter, longer) designed and procured. Both cryostats have been received from the vendor (Ability Engineering & Technology); one has been installed.
- Integration with cryo-system for VTS-2 to begin soon.
VCTF Upgrades

Additional Pumping System

- 4 new Kinney pumps, each with 4 g/sec capacity
  - Add to existing 4 g/sec pump for a total of 20 g/sec
- Manifold to allow up to 4 pumps to pump on any of 3 Dewars
- Can pump 2 Dewars at a time
  - Up to 3 pumps on one Dewar
- No longer interference with SC Magnet testing program
VCTF Upgrades

Multiplexed RF System

- RF/DAQ system modified so that RF and instrumentation signals to/from each of 3 cryostats can be monitored/controlled/recorded by the existing system
- Independent HP amplifiers for each cryostat, to minimize losses through a distribution network
- Modified to provide capability for 650MHz operation at any cryostat
- Will share existing external radiation shielding block
  - Only one RF test in progress at a time
  - Insufficient real estate to add individual shielding blocks
VCTF Upgrades

Multiplexed RF System

1300MHz to 650MHz frequency conversion module

Dewar RF signal switching module
VCTF Upgrades

Staging Area

- A permanent staging area accommodating inserts for all 3 cryostats (2 each) is planned.
- HEPA FFU’s installed to provide clean laminar flow
- Each “station” to have connections for roughing vacuum and vacuum gauge readout
- Conceptual design exists, preliminary vendor quotes/information available
- Installation planned for early CY12, pending completion of VTS-2 and VTS-3 installation and integration.
VCTF Upgrades

Staging Area

Limited crane hook-height requires “side-loading” vs “top-loading” option.

Plastic curtain interior walls

HEPA FFU’s.
VCTF Upgrades

He Gas Storage/Improved He Liquefaction

• Additional GHe storage tanks to eliminate potential delays in boiloff or return of LHe from cryostats
• Can dedicate one tank for “dirty” He in case of contamination w/out risking cryoplant downtime
• Liquefaction studies performed in 2008 and 2010 – identified problems limiting LHe production, solutions underway.

These improvements will ensure that testing is not delayed due to insufficient LHe supply or gas storage limitations – helping to maximize the throughput increase from the added cryostats.
VCTF Upgrades

Increased He Recovery/Purification Capacity

- Additional 60 g/sec Mycom compressor w/oil-removal system
- Dual 60 g/sec purifier
  - (one active, other regenerating)
- Full purification of all returned He gas (only partial before)
- Allows purification of entire cryoplant He inventory if needed

Mycom compressor
Dual purifiers
VCTF Upgrades

- All of the improvements and upgrades to the VCTF will provide a facility capable of performing ~200 cavity tests/year.

- We will be able to test 1300 and 650MHz elliptical cavities and 325MHz spoke-type cavities.

- VCTF operations will be completely de-coupled from other SC device test operations in IB1.

- We expect that the 2\textsuperscript{nd} cryostat (VTS-2) will be operational by the end of this calendar year; the cryoplant upgrades, and integration of VTS-3, will follow in CY 2012.
Highlights of Cavity R&D

The VCTF exists in order to fulfill a critical mission need in the SRF program

- Production-style testing of 9-cell ILC cavities, for use in a cryomodule

- Cavity testing as part of an R&D program
  - Cavity processing facility commissioning
  - Quench localization
  - Defect repair
  - Process optimization, alternate processes
  - Studies of cavity performance
Cavity Processing Facility Commissioning

• Joint FNAL/ANL cavity processing facility completed in late 2008/early 2009
• Single-cell cavities used to evaluate performance of facility – initially HPR & assembly systems/procedures, then EP
• Field emission major performance limitation
• Eventually improvement to processes and tooling helps reduce contamination
• Single-cell cavities achieve FE-free performance, and reach high gradients
• 9-cell cavities still show FE limitations; additional improvements made, and performance improves
Highlights of Cavity R&D

Cavity Processing Facility Commissioning

Examples of early SC test w/heavy field emission/field emission loading.
Highlights of Cavity R&D

Cavity Processing Facility Commissioning

Field emission greatly reduced, cavities in some cases now limited by HFQD/RF power (no capability to do 120°C BC bake yet).

AES004 now improved (see previous slide) with additional HPR, and 120°C bake – exceeding ILC specs.
Highlights of Cavity R&D

Cavity Processing Facility Commissioning

Cavity performance becoming reproducible. FNAL/ANL cavity processing facility now capable of producing high quality SC cavities.

Fermilab 1-cell Statistics

ANL/FNAL cleanroom starts
Highlights of Cavity R&D

Cavity Processing Facility Commissioning

Moving on to 9-cell cavities, field emission is still a problem…
Highlights of Cavity R&D
Cavity Processing Facility Commissioning

Improvements implemented – among them:

- Ultrasonic cleaning without cavity cage
- New preassembly procedures
  - Stricter assembly practice
  - Bolt tightening after all ports are sealed
- Final assembly procedures modified
  - Minimized the human activity after final HPR
  - Piloting bolts
- Evacuation
  - Slow evacuation improved (mass flow control)
Highlights of Cavity R&D

Cavity Processing Facility Commissioning

Progress is made – while some FE remains, the cavity reaches the ILC spec and is not limited by FE.

Eventually, FE-free performance is achieved. The facilities, procedures, and tooling at the FNAL/ANL cavity processing facility are capable of achieving ILC-level performance. But constant vigilance is required!
Quench Localization

Quench localization is a vital part of understanding cavity performance limitations – once we know where a cavity is quenching, we can look further to try and determine why it is quenching.

Two techniques are currently used at the VCTF:

- Fast Thermometry
- Second Sound
Highlights of Cavity R&D

Quench Localization – Fast Thermometry

- Two bands of 8 Cernox sensors applied to cell equator(s)
- Also capable of utilizing “flying” (loose) sensors
- Resistance (voltage) read out using NI fast-sampling (1-10kHz) multi-channel A/D card
- Signals amplified and conditioned in custom module
- Data is filtered to reduce noise
- Sensitive to < 1mK fluctuations
Highlights of Cavity R&D
Quench Localization – Fast Thermometry

Examples of temperature “spikes” during quenches.

Relative amplitudes between sensors help to localize the quench origin.
Quench origin observed to shift between two locations in superfluid He. Quenching at 40 MV/m (single-cell cavity). Red and blue peaks alternate in amplitude – quench origin shifting from one side of green peak sensor location to the other.
Highlights of Cavity R&D
Quench Localization – Fast Thermometry

Optical inspection of cavity interior surface guided by FTS quench localization often leads to observation of a “defect”. Localized “repair” can then be considered.

Examples:

- 230μm diameter defect on cavity TB9ACC017
- 200μm diameter defect on cavity TB9AES013
Highlights of Cavity R&D

Quench Localization – Second Sound

- Identical system/sensors as developed/used at Cornell
- Typically 8 sensors placed around 9-cell cavity
- Pre-amp located on top plate (reduce parasitic capacitance of long cables)
- Signals read out using 24–bit A/D card

Second sound (OST) sensors mounted on PC boards, fastened to posts of cavity support cage. Sensors face cavity.
Highlights of Cavity R&D

Quench Localization – Second Sound

Typical signal from OST’s. Red trace is cavity transmitted power (field).

Time delay converted to distance from signal (thermal) source, triangulation used to localize quench origin – just as is done at Cornell.
Defect Repair – Localized Grinding (collab w/KEK)

- Cavity TB9AES003 originally quench limited to 20MV/m.
- Optical inspection performed at KEK revealed defect at quench origin (determined by thermometry at FNAL).
- KEK performed local repair (grinding) and EP/HPR of cavity, then sent to FNAL.
- Additional HPR performed at FNAL, then vertically tested.
Highlights of Cavity R&D
Defect Repair – Localized Grinding (collab w/KEK)

Cavity now essentially reaches ILC spec – no longer quenching @ 20 MV/m. Defect leading to low-field quench removed.

Cavity residual surface resistance ~ 5nΩ. Overall surface of high quality.
Defect Repair – Laser Re-Melting

Improve cavity quench performance by “melting” a defect/pit, so that the pit profile changes and, presumably, magnetic field enhancement (leading to early quench) is reduced.

Cavity TE1ACC003 had a 400µm diameter 60µm deep pit. After laser melting and 50µm EP, pit was 700µm diameter, but only 30µm deep.

Before laser melting

After laser melting
Highlights of Cavity R&D
Defect Repair – Laser Re-Melting

After laser melting, and two EP processes (for a total of about 50\(\mu\)m), performance improved from 36 to 40+ MV/m. Quench location consistent with site of re-melt.

Next step is to complete the process on a 9-cell cavity (TB9ACC017).
Highlights of Cavity R&D

Alternate Process – Centrifugal Barrel Polishing
(aka Tumbling/CBP)

CBP, originally developed by KEK, shows promise as a technique that can be used to:

- Eliminate the so-called “damage layer” of and produce a smooth surface on a fresh Nb cavity, thereby eliminating (bulk) EP
- Remove imperfections/defects/”bad” weld seams

Initial R&D efforts have shown that:

- CBP can produce mirror-like finishes
- Cavity $Q_0$ may be improved (increased)
- Some EP (20-40 $\mu$m) is needed to remove “embedded media”
Highlights of Cavity R&D
Alternate Process – CBP

- CBP can achieve mirror-quality surface finishes.
- Can eliminate all but ~40-50 μm of EP processing (so far).
- Tumbled cavities typically require longer H degassing treatment (3hrs @ 800C vs 2hrs for bulk EP’d cavity).

Cavity performance can be as good or better than “standard” EP processing recipe.
Highlights of Cavity R&D

Alternate Process – CBP

Single cell cavity, received 120μm material removal via CBP, then ~40μm EP, H-degassing (3hrs @ 800°C) then 20μm EP, HPR, and 120°C bake.

Cavity performed superbly – reaching 40+ MV/m, with high Q₀. Residual surface resistance ~4.5nΩ
Highlights of Cavity R&D
Alternate Process – CBP/Pit Repair

Cavity TB9ACC015 limited to 19MV/m (quench) during test at JLab. Large (200μm) pit in cell 3.

Pit removed by CBP & EP:

Before CBP

After CBP and 40μm EP
Highlights of Cavity R&D
Alternate Process – CBP/Pit Repair

Cavity improved from 19 MV/m to 35MV/m (meeting ILC specs!)
Highlights of Cavity R&D
Alternate Process – CBP/Weld Seam Improvement

Cavity TE1CAT002 limited to 22 MV/m. Had very poor weld quality, voids, etc.

Before CBP – rough irregular weld seam

After CBP – most traces of weld seam removed, though some defects remain
Highlights of Cavity R&D

Alternate Process – CBP/Weld Seam Improvement

Overall improvement in $Q_0$ and increase in quench field to 24MV/m. Equatorial weld quality (voids) still probably dominating performance.
Highlights of Cavity R&D
Alternate Process – Dressed Cavity EP

Dressed cavity TB9AES002 repeatedly limited to 20 MV/m by quench during vertical test (had reached 32MV/m un-dressed). FE not an issue. Only remedy appeared to be additional EP.

Try it w/out removing He vessel.

Main modifications were anode connection at beam tubes (instead of individual cells) and fewer # of TC’s for monitoring cavity temperature during EP (only on beam tubes and cell #3).
Highlights of Cavity R&D
Alternate Process – Dressed Cavity EP

After dressed cavity EP – cavity reaches 28+ MV/m, limited by HFQD.

Cavity recently received low-temperature bake (120°C) @ JLab, will be tested shortly. Expect performance to improve.

Before dressed cavity EP – limited to 19.8 MV/m (quench) w/ out FE.
Highlights of Cavity R&D

Medium-Field Q-slope Studies

There is interest in understanding how the so-called medium-field Q-slope is affected by operating temperature and cavity surface preparation.

This could potentially influence the choice of cavity processing method and operating temperature for a CW Linac such as that proposed for Project-X.

As time permitted, sets of $Q_0$ vs $E$ measurements were performed on a number of cavities, at the temperatures 2.0, 1.9, 1.8, 1.7, and 1.6K.
Highlights of Cavity R&D
Medium-Field Q-slope Studies

ILC-TB9RI022 - Q vs E

ILC-TB9RI021 - Q vs E

ILC-TE1AES003 - Q vs E

ILC-TE1ACC005 - Q vs E
Highlights of Cavity R&D
Medium-Field Q-slope Studies

Preliminary analysis seems to indicate differences between 9-cell and single-cell cavities and also surface preparation methods.

Analysis is ongoing – to be reported more fully @ SRF2011
Highlights of Cavity R&D

In addition to the highlights presented, there are other R&D activities presently underway or just beginning, for which the VCTF will play an integral part:

- Effects of externally applied magnetic field on quench field and quench recovery
- Measurements of flux trapping during quench, and quench origin migration
- Effect of progressive HF rinses on removal of oxides, and (re-)appearance of HFQS in baked cavities
- Efficacy of new (industrial) surface preparation processes (Cabot (CMP), Faraday Technologies (bipolar pulse EP))
- Temperature dependence of surface resistance as a function of gradient/magnetic field
- Development of a single-cell T-Map system (Cornell/Jlab style)

Much to do… additional test cryostats will be a most welcome upgrade!
Acknowledgments

Numerous dedicated and talented individuals have contributed to the development/operation/upgrade of the VCTF and the pursuit of the R&D described here:

**VCTF:**

**Cavity R&D:**
Thank You for Your Hospitality and Attention!