Recent Progress in the Superconducting RF Program at TRIUMF/ISAC

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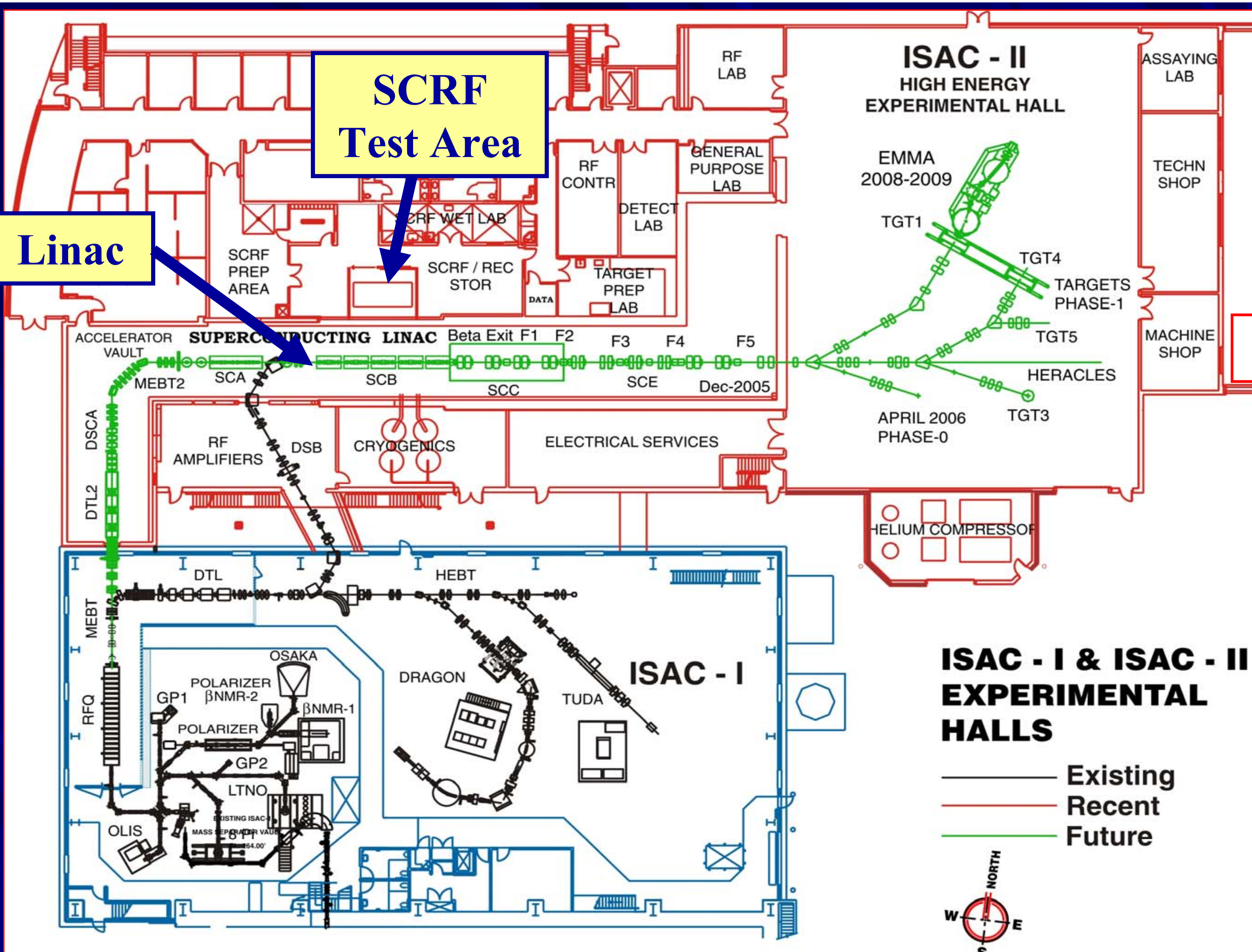
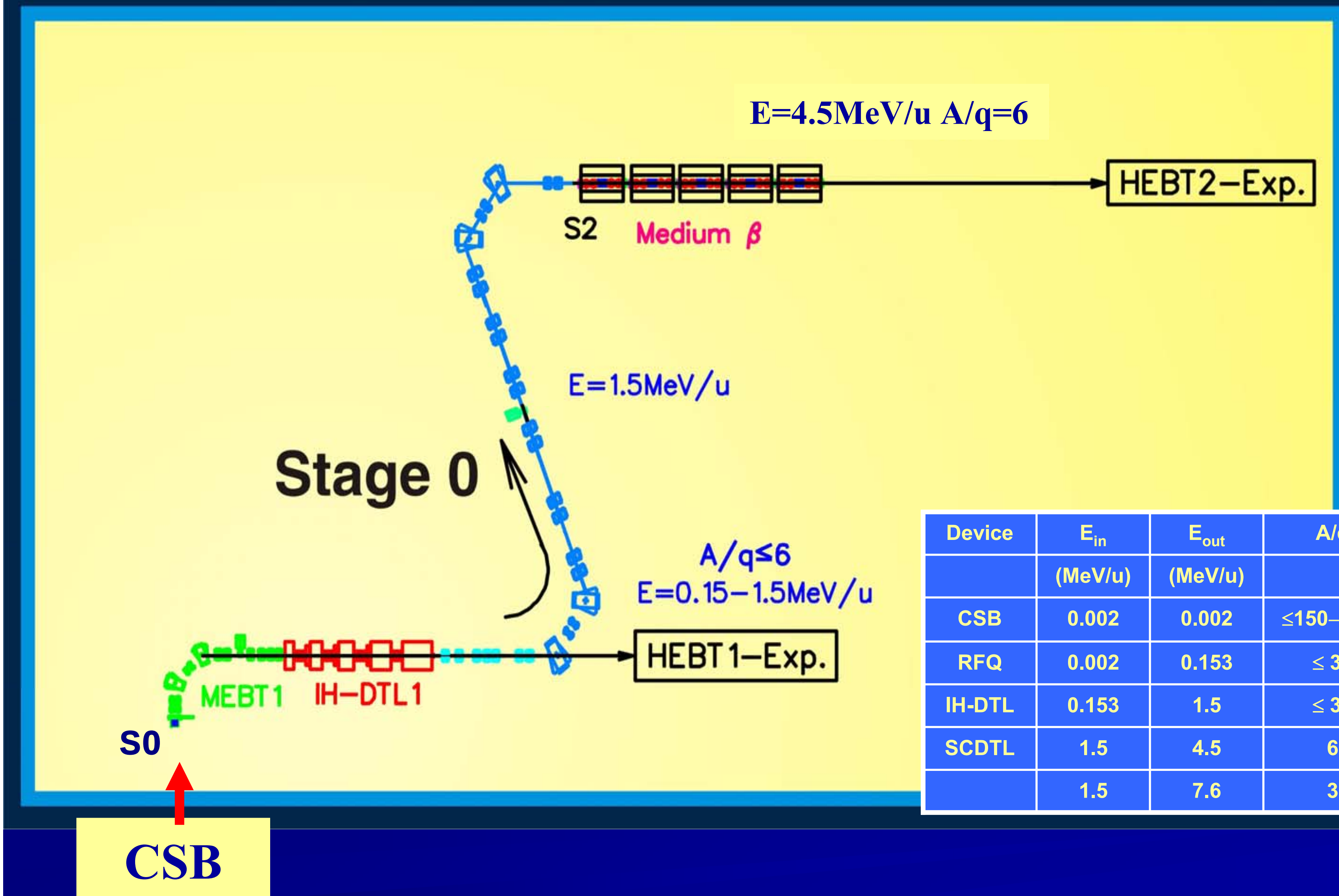
Outline:

- Overview of ISAC-II Linac
- Medium Beta Cryomodule
  - Summary of SC solenoid experience
- Cavity Testing Results
- Acceleration Studies


SCRF
Test Area
Linac
ISAC - II
HIGH ENERGY
EXPERIMENTAL HALL
RF
LAB
ASSAYING
LAB
TECHN
SHOP
MACHINE
SHOP
EMMA
2008-2009
TGT1
TGT4
TARGETS
PHASE-1
TGT5
HERACLES
TGT3
APRIL 2006
PHASE-0
GENERAL
PURPOSE
LAB
RF
CONTR
DETECT
LAB
TARGET
PREP
LAB
DATA
SCRF WET LAB
SCRF / REC
STOR
SCRF
PREP
AREA
ACCELERATOR
VAULT
SUPERCONDUCTING LINAC
Beta Exit F1
F2
F3
F4
F5
MEBT2
SCA
SCB
SCC
SCE
Dec-2005
DSCA
DTL2
RF
AMPLIFIERS
DSB
CRYOGENICS
ELECTRICAL SERVICES
HELIUM COMPRESSOR
DTL
HEBT
MEBT
RFQ
OSAKA
POLARIZER
βNMR-2
GP1
βNMR-1
POLARIZER
GP2
LTNO
OLIS
DRAGON
TUDA
ISAC - I
ISAC - I & ISAC - II
EXPERIMENTAL
HALLS
Existing
Recent
Future
NORTH
W
E
S

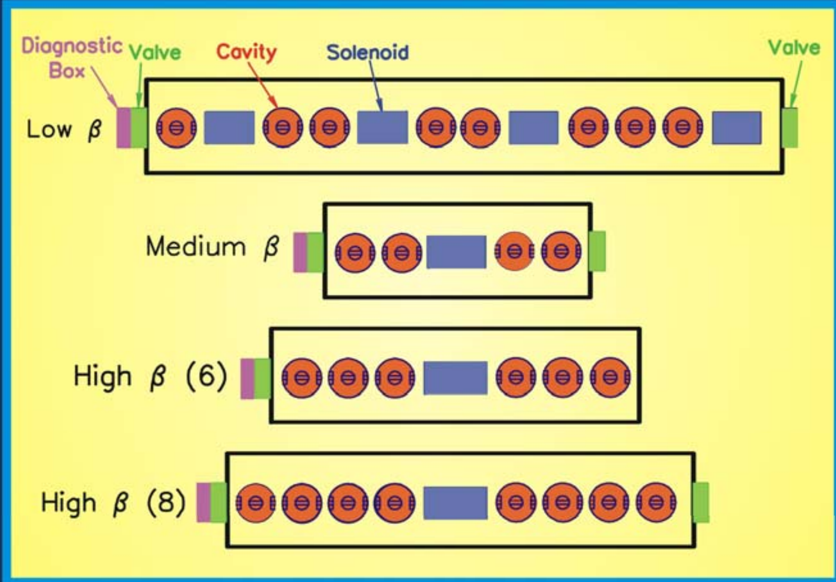
Stage 0 - 2005



Device	E_{in}	E_{out}	A/q	V_{eff}
	(MeV/u)	(MeV/u)		(MV)
CSB	0.002	0.002	≤150→≤30	-
RFQ	0.002	0.153	≤ 30	4.5
IH-DTL	0.153	1.5	≤ 30	7.5
SCDTL	1.5	4.5	6	18.3
	1.5	7.6	3	18.3

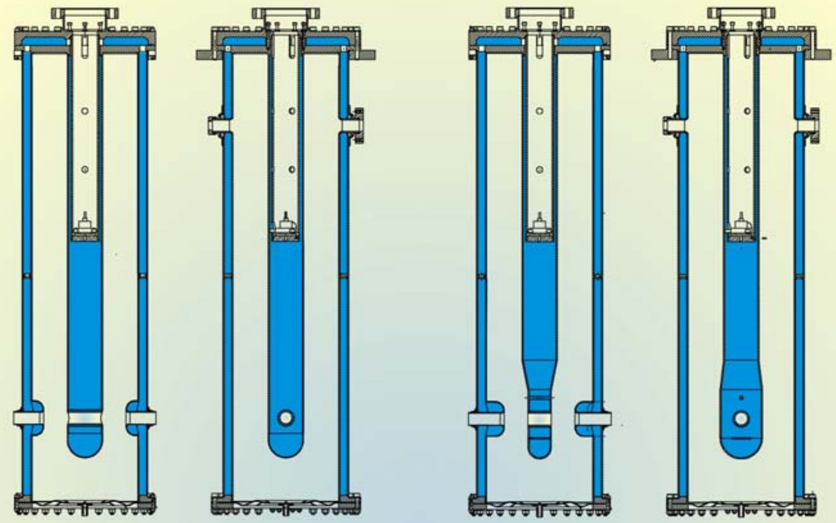
ISAC-II SC Linac

ISAC-II Cryomodules



Prototype Cavity

Medium Beta Cavities



(a) Nominal (β=7.1%) (b) Flat (β=5.7%)

freq=106.08MHz

$E_p/E_a \simeq 5$

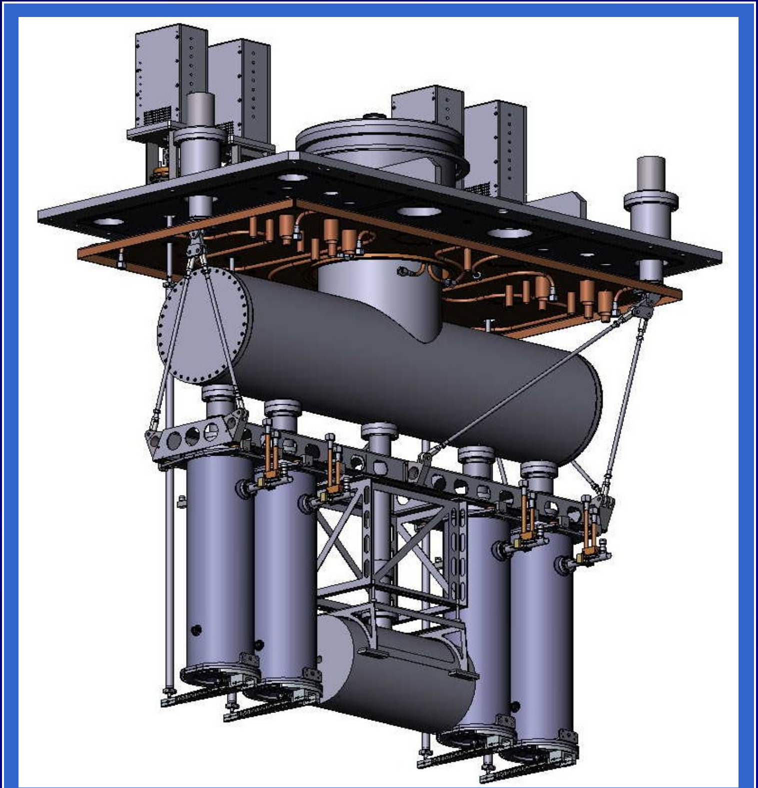
$H_p/E_a \simeq 100$ G/(MV/m)

$U/E_a \simeq 0.09 J/(MV/m)^2$

$\Gamma \simeq 19\Omega$

Medium Beta Cryomodule

- 2x2x1m stainless steel box vacuum vessel
- LN2 cooled copper sheet used as thermal shield
- Mu metal between vacuum tank and LN2 shield
- Cold mass suspended from lid on three support pillars
- Four cavities Ep=30MV/m
- One SC solenoid @ 9T
- V_{eff}=4.3MV

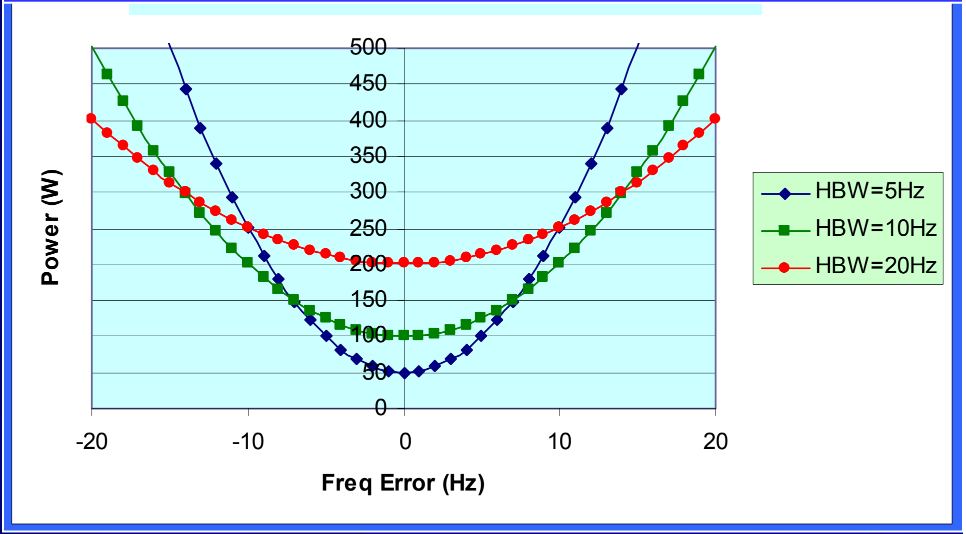


Lid Assembly in Assembly Frame

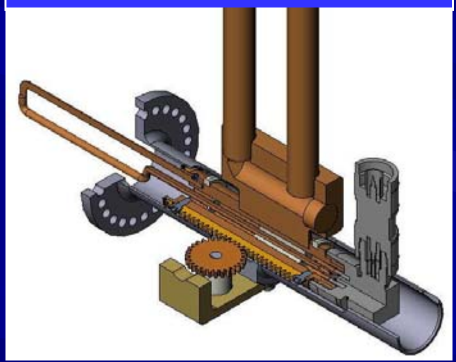
RF Systems

- **RF power**
  - Provide useable bandwidth by overcoupling
  - Require P_f=200W at cavity for $f_{1/2}$=20Hz at E_a=6MV/m, β=200
- **Coupling loop**
  - Developed LN2 cooled loop
  - <0.5W to LHe for P_f=250W
- **Mechanical tuner**
  - Precise (0.3~Hz), fast (>50Hz/sec) tuner with dynamic range of 8kHz and coarse range of 32kHz
- **Tuning plate**
  - Spun, slotted, `oil-can' tuning plate to improve tuning range

Forward power required for Ea=6MV/m and given bandwidth

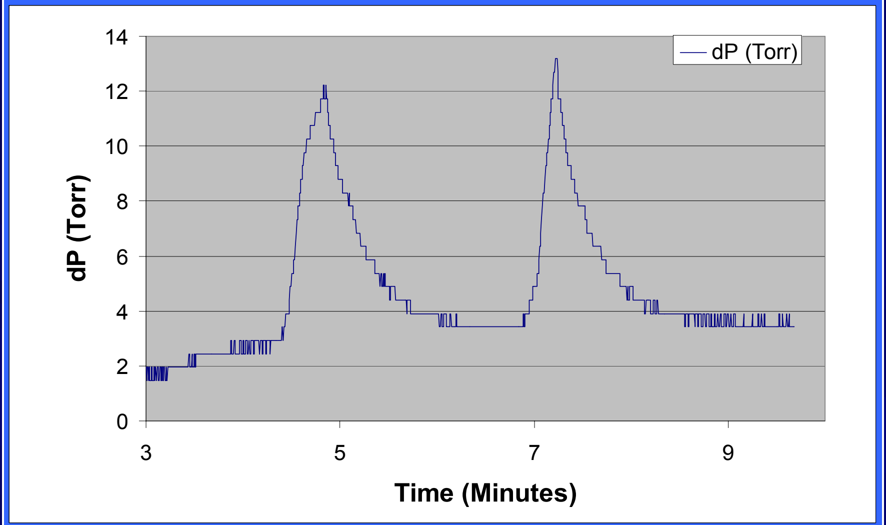


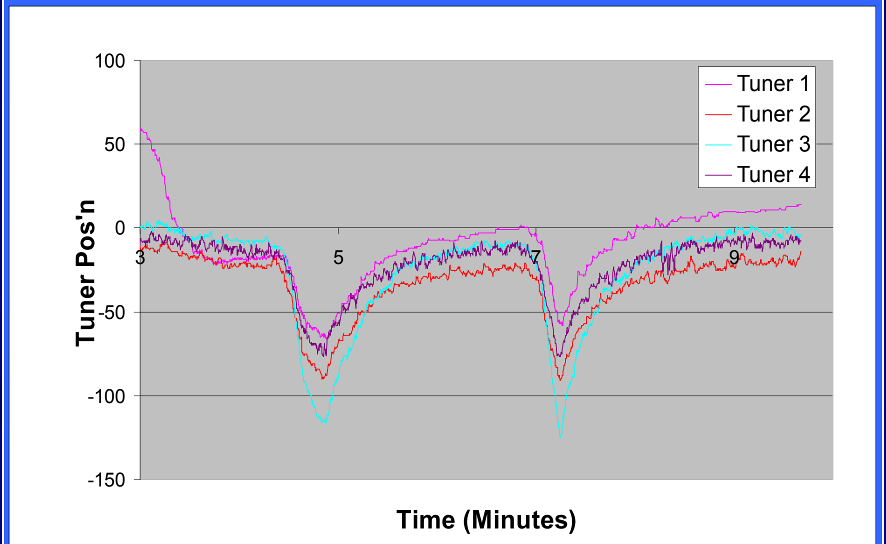
Coupling Loop

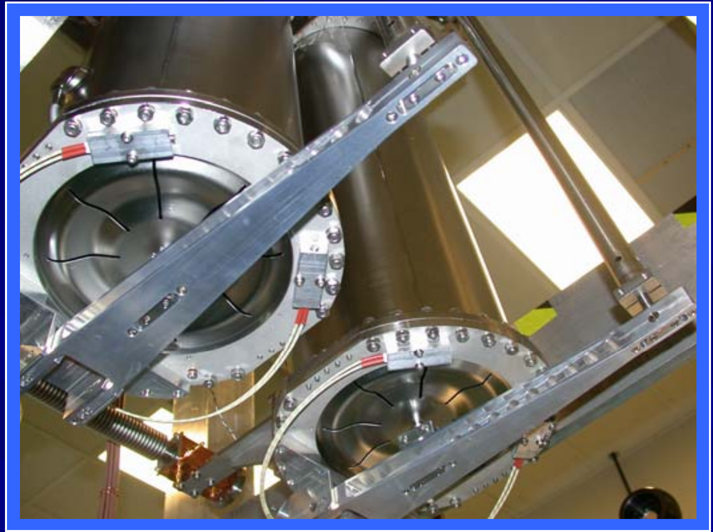


Mechanical Tuner

Tuner Response with Four Cavities



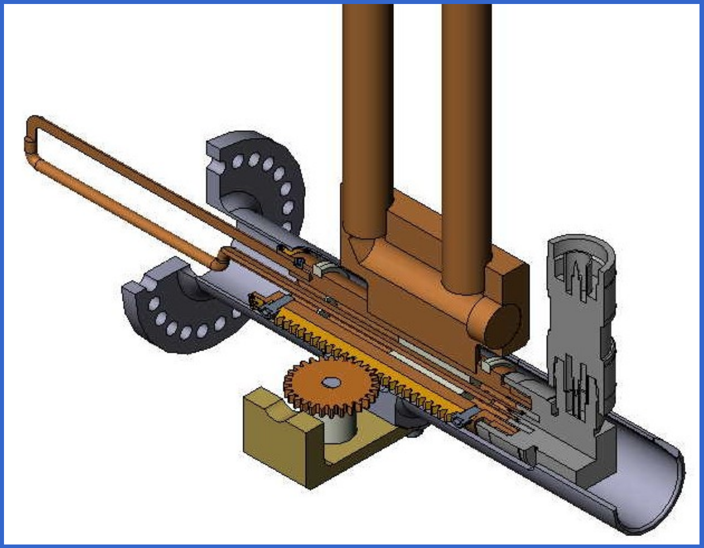




- ❑Lever mechanism with zero backlash hinges and stiff rod connected to precision linear motor (Kollmorgan) in air
- ❑All four cavities locked to ISAC-II Specifications
  - ➢Ea=6MV/m (Ep=30MV/m) and 106.08MHz
  - ➢P_{cav}~6W, P_{for}~250W, β~170
- ❑Helium exhaust valved off to force pressure fluctuation

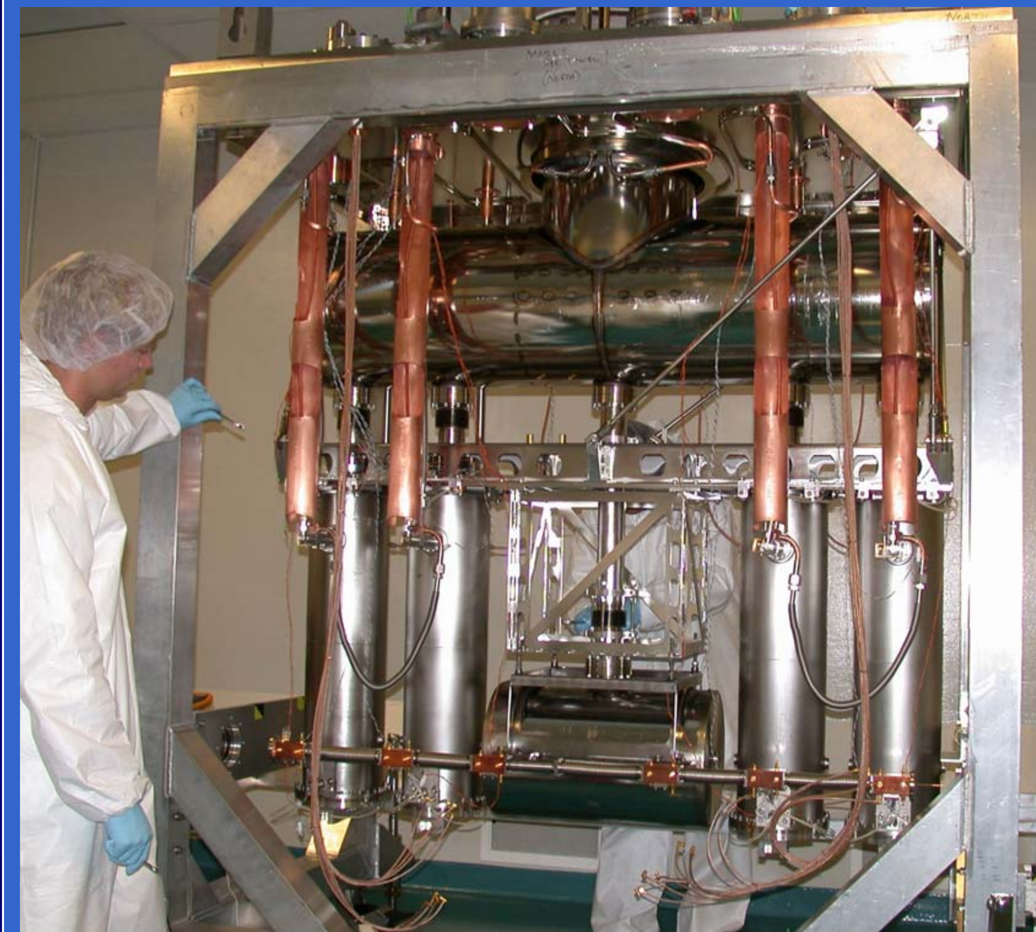
Coupling Loop with Direct Cooling

- ❑Developed from INFN Legnaro adjustable coupling loop
- ❑Modifications
  - ✓Stainless steel body for thermal isolation
  - ✓Copper outer conductor thermally anchored to copper LN2 cooled heat exchange block
  - ✓Aluminum Nitride dielectric inserts thermally anchor the inner conductor to the outer conductor
  - ✓Removed fingerstock to control microdust
- ✓Achieved <0.5W helium heating with Pf=250W



Cryomodule Cold Tests

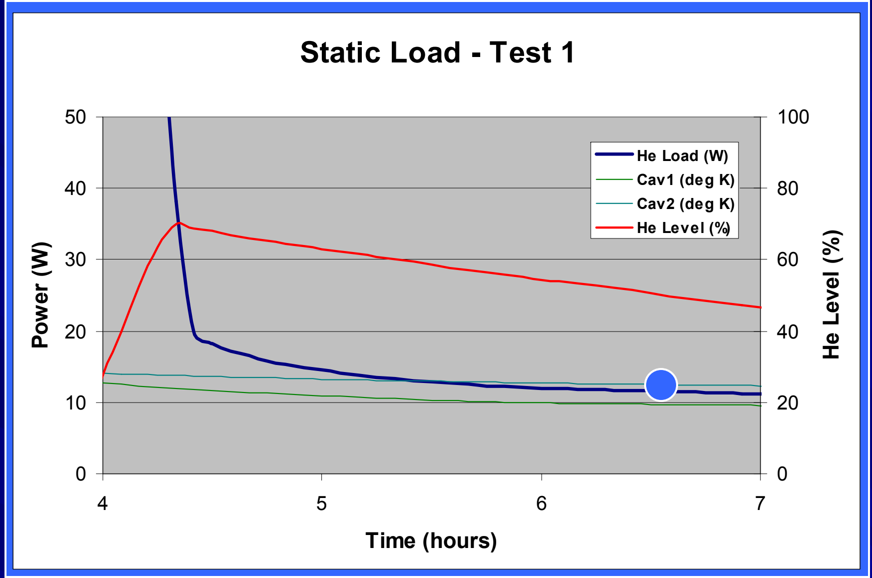
SCB3 Cryomodule Assembly Before Test 2

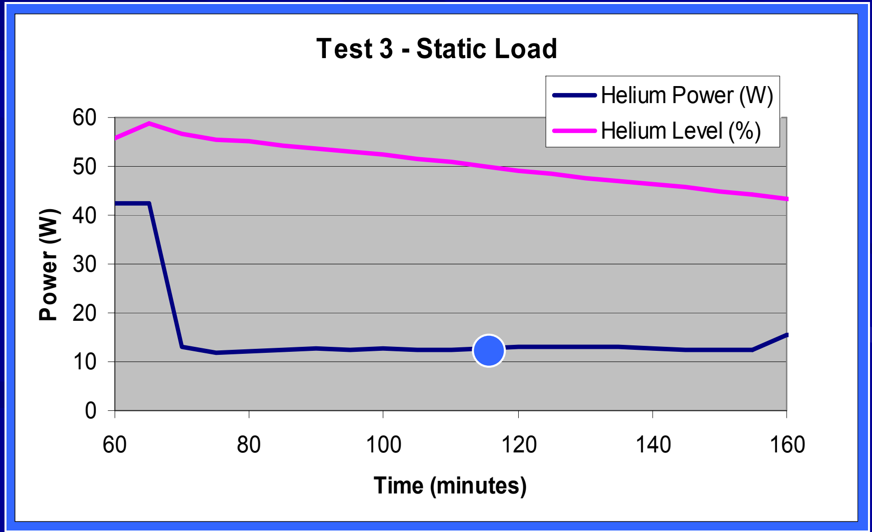


- First Cooldown (SCB3)
  - April 2004
  - Alignment and Cryogenic studies
- Second Cooldown (SCB3)
  - June 2004
  - Rf studies (alignment check)
- Third Cooldown (SCB3)
  - Oct. 2004
  - Final rf studies
  - Remote operation
  - alpha acceleration
- Fourth Cooldown (SCB1)
  - March 2005
  - Alignment, Cryogenic, and rf

Cryomodule Static Load – Test 1, 2, 3

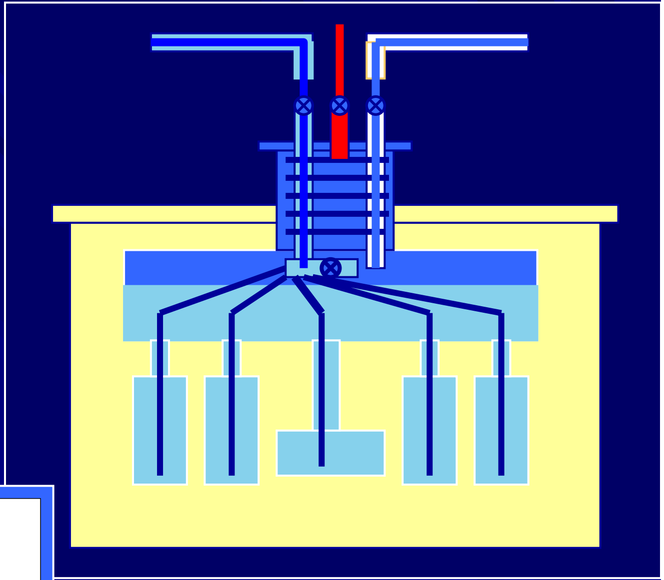
- April 25 – First cooldown
  - No rf or solenoid cables
  - **11W** static load
- July 2 – Second cooldown
  - Rf/solenoid/alignment cables
  - **16W** static load
- Nov. 3 – Third cooldown
  - Final configuration
  - **13W** static load

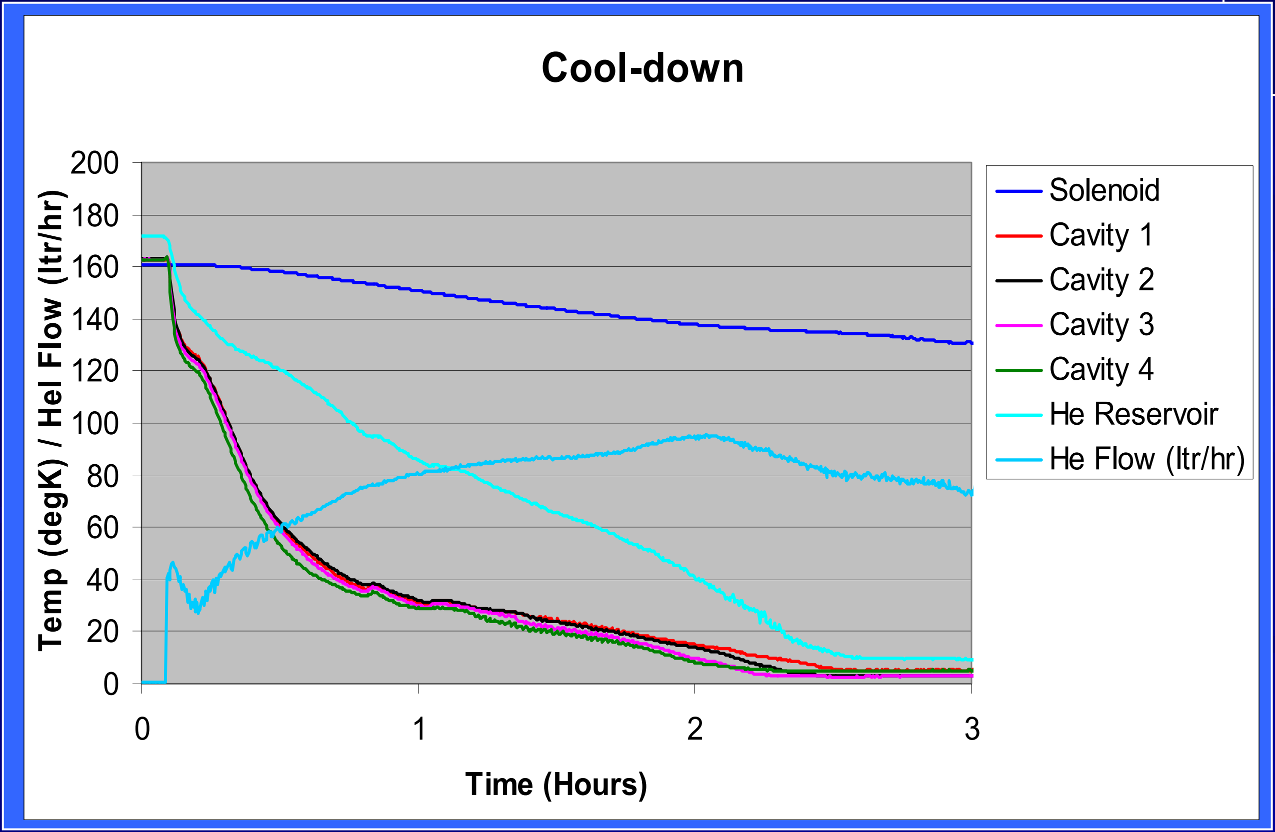




Cryomodule Cooldown

- Cryomodule pre-cooled with LN2 and further cooled with LHe through a parallel arrangement of small tubes, `spider', from common manifold
- Manifold and `spider' worked well to cool cavities uniformally
- The solenoid, due to larger mass and different geometry, takes ~10 hours @ 75ltr/hr to cool





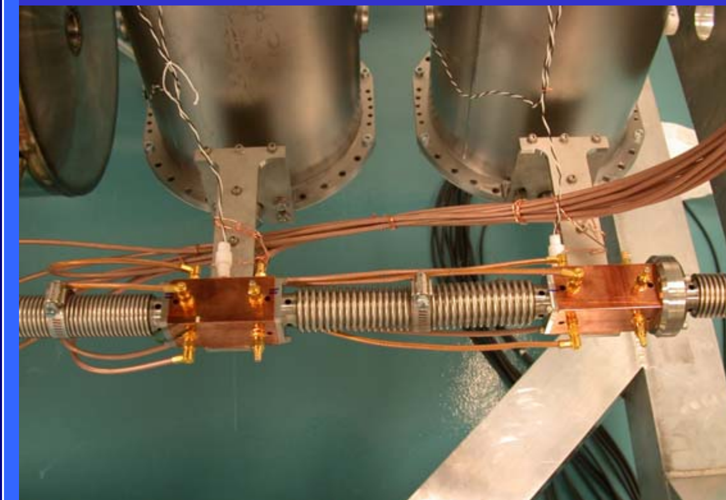
Cryomodule Alignment

- ❑ **the tolerance on solenoid and cavity misalignments are ±200 μm and ±400 μm respectively**

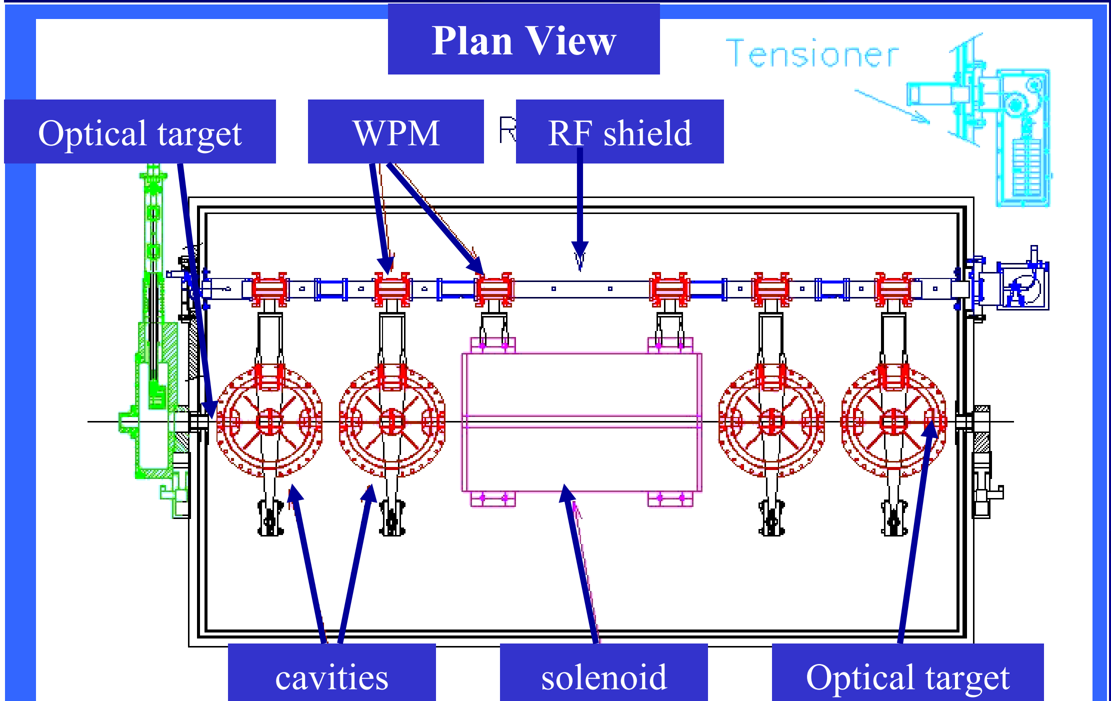
- ❑ we have collaborated with INFN Milano on the development of a Wire Position Monitor for cold alignment with precision of 20 **μm**

  - ➢Stripline monitor attached to each device driven by rf signal along a reference wire

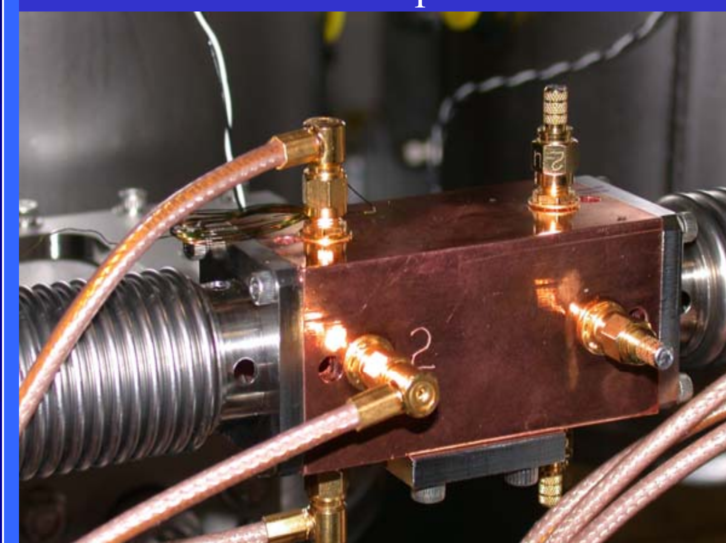
WPM Monitors on Cavities



Plan View



Wire Position Stripline Monitor



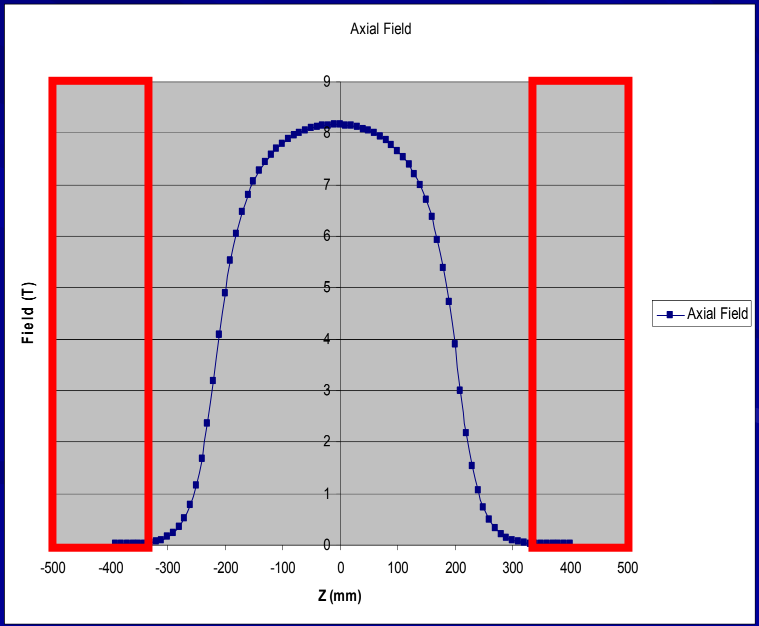
Superconducting Solenoids

See ThP40

- Focussing in the SC Linac is provided by superconducting solenoids (B≤9T)
- End fringe fields controlled with active `bucking' coils ($B_{cavity} \leq 0.1T$)
- Production Medium and high beta solenoids in fabrication at Accel
  - See table for specifications

Prototype Solenoid at Accel

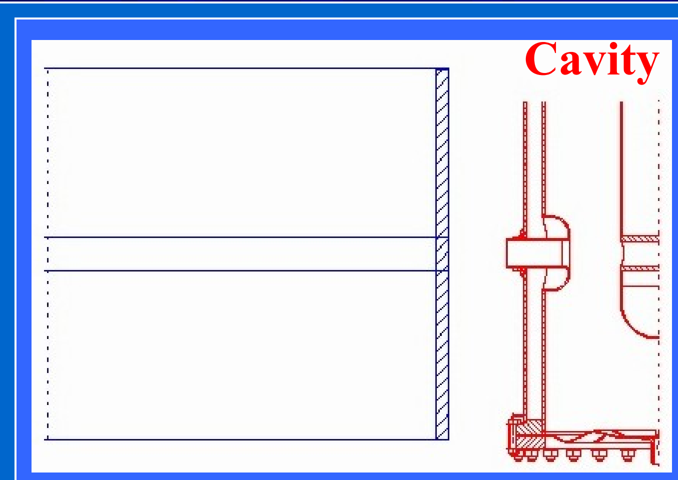
	Low β	Med β	High β
Field	9T	9T	9T
Bore	26mm	26mm	26mm
Number	4	5	3
Eff. Length	16cm	34cm	45cm

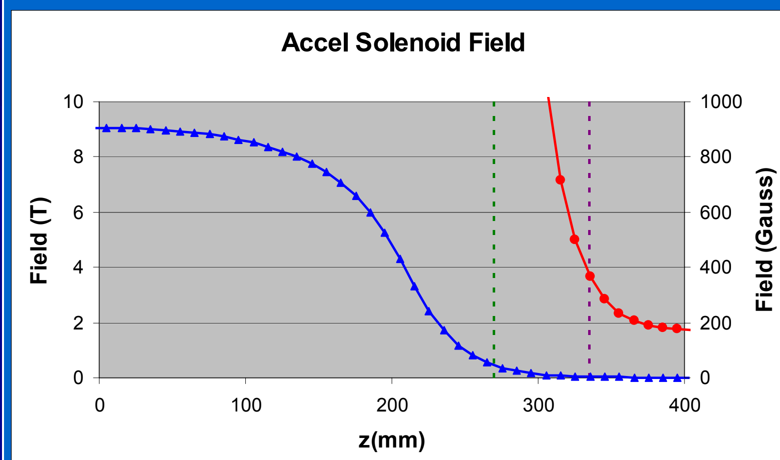


See ThP40

Solenoid – Test 2

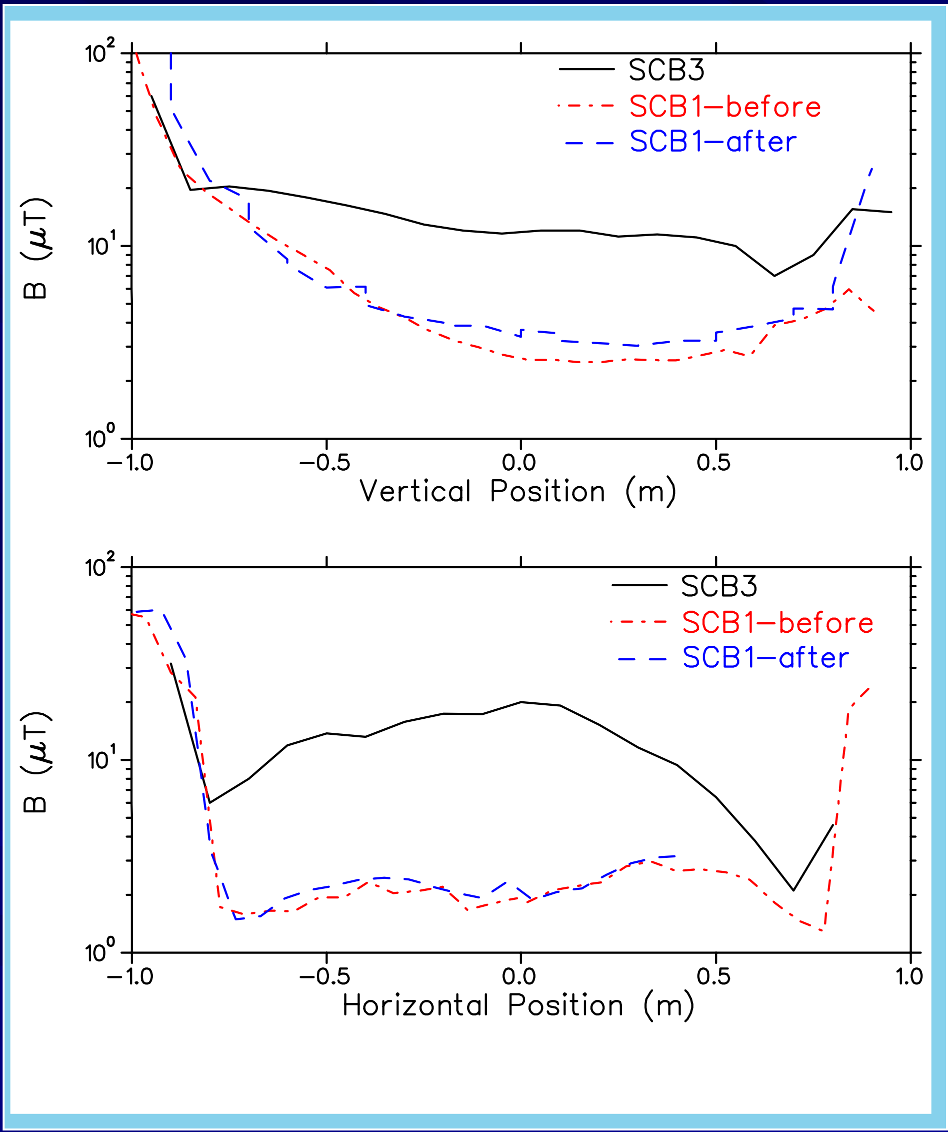
- Base Q's measured before solenoid test
- Ramp up solenoid to 9T
    - Cavities 2 and 3 on
    - No quench of cavities or solenoid
    - No change in cavity Q
- Cold mass warmed above transition
- Q's measured after second cooldown
    - No change; Q>1e9
    - Residual field tolerable
- Field measurements after test showed that some magnetization of environment occured





Magnetic Mapping of Cryomodule

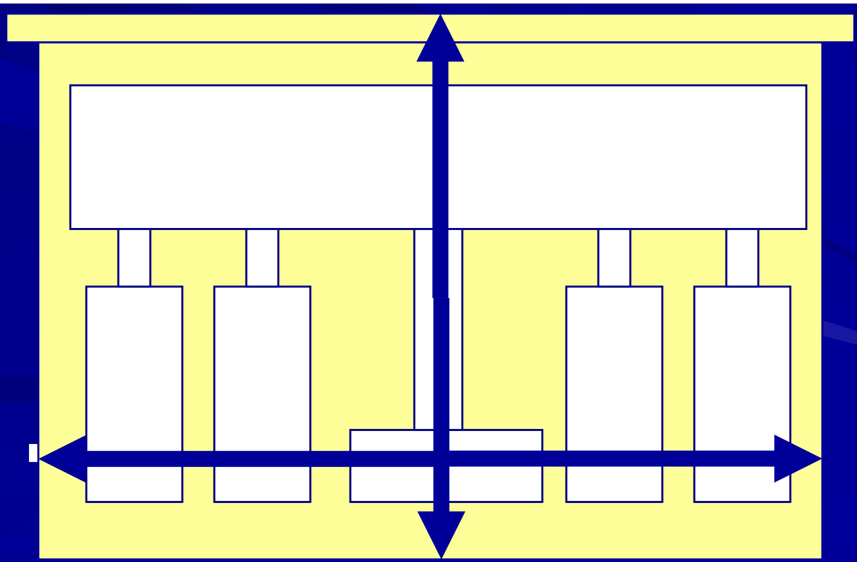
See ThP40



Mapped the internal magnetic field for

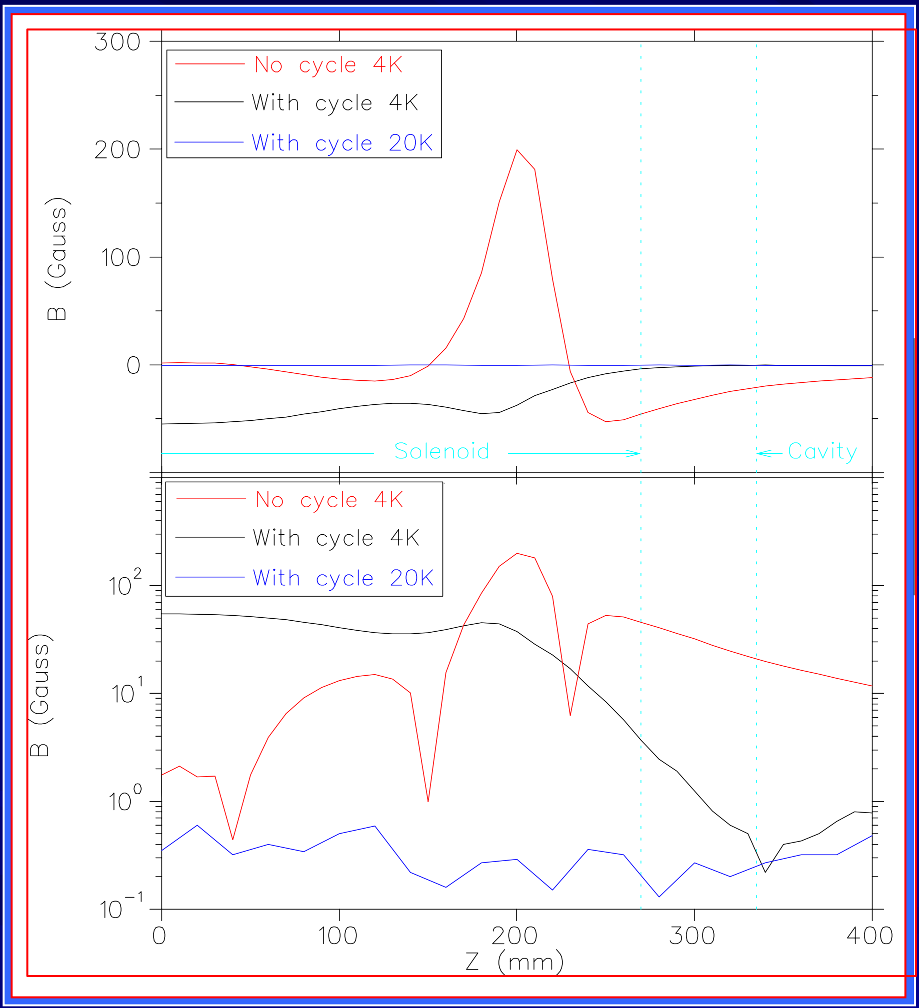
1. SCB3 after solenoid powered then warmed (no hysteresis cycle)
2. SCB1 before powering the solenoid
3. SCB1 after powering the solenoid and with hysteresis cycle

Hysteresis cycle required to reduce memory of solenoid



Frozen Flux

See ThP40



Mapping data* for ISAC-II Solenoid

- Solenoid is brought to 9 T and

a) Ramped to zero with no cycle at 4K

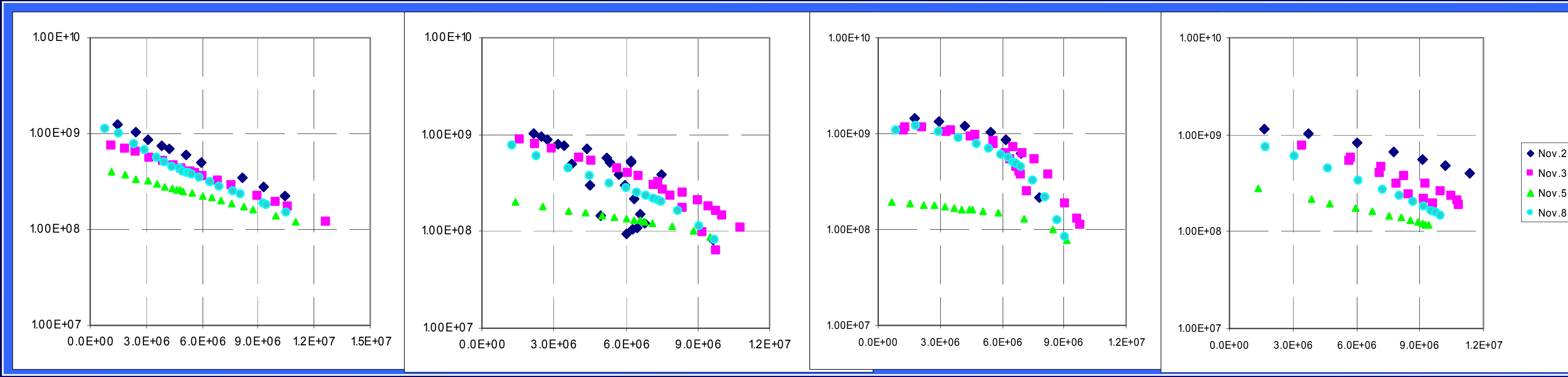
b) Taken to zero through hysteresis cycle at 4K

c) Ramped to zero and warmed to 20K

Frozen flux in solenoid produces a large (20G) field in cavity region when no hysteresis cycle is used. Cycling the magnet does reduce the field at the cavity but only warming the solenoid can eliminate the field.

* Data taken by Accel

TEST3: Q –curves of the cavities in the Cryomodule during four days rf test

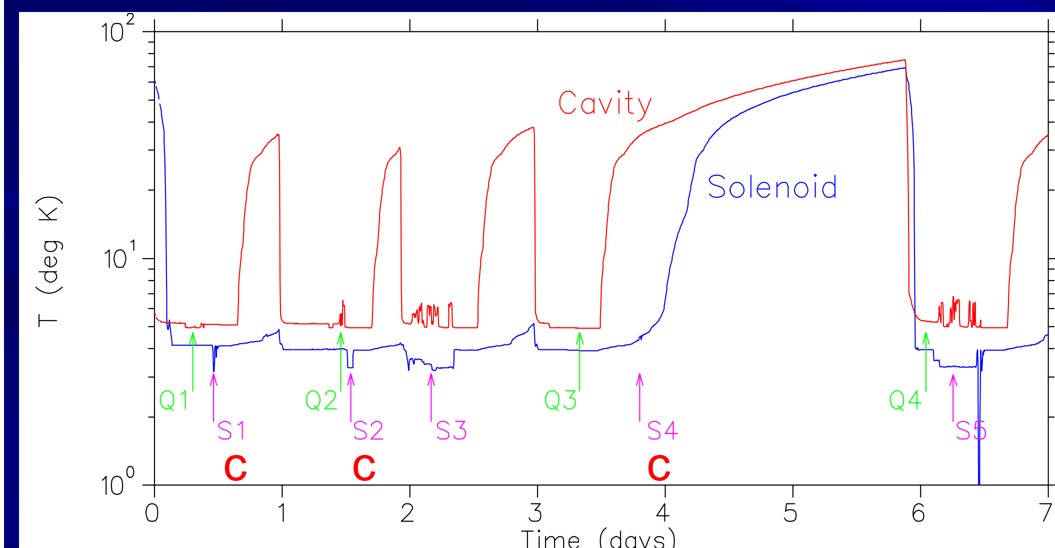


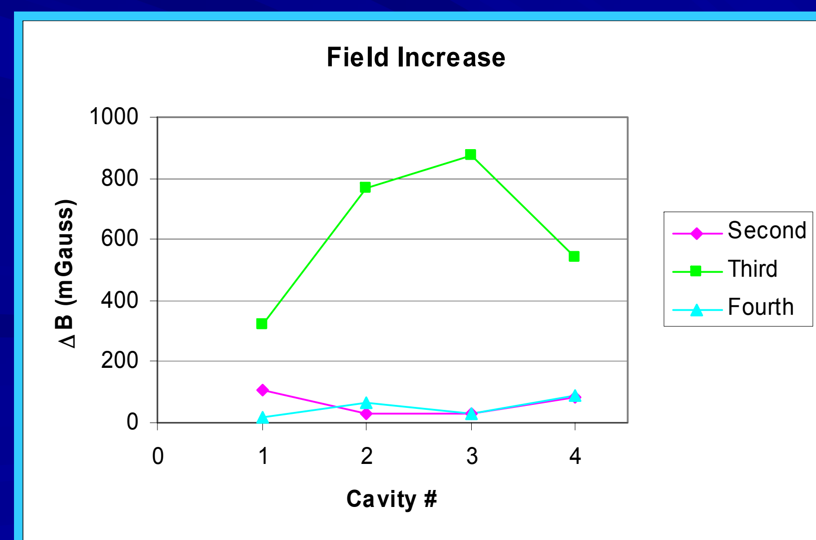
Cavity #1 Cavity #2 Cavity #3 Cavity #4

Cavities warm overnight but solenoid doesn't

- On Day 1 and Day 2 the solenoid is hysteresis cycled
- On Day 3 no cycle and we get a large Q-drop

$$\Delta B\left(mGauss\right) = \frac{\Delta R_{mag}\left(n\Omega\right)}{0.3\cdot\sqrt{f\left(GHz\right)}}$$





Summary of Cavity Testing

See TuP36

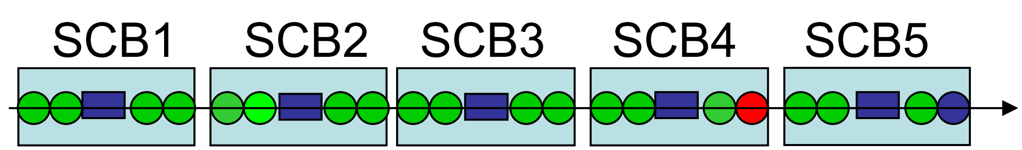
Flat Cavities

- SCB1
  - Cav 5√, 6√, 8√, 10√
- SCB2
  - Cav 7√, 9√, 11√, 12√

Round Cavities

- SCB3
  - Cav 1√, 2√, 3√, proto√
- SCB4
  - Cav 13√, 4√, 16√ ,14x
- SCB5
  - Cav 17√, 18√, 19√, 20
- Spare
  - Cav 15x

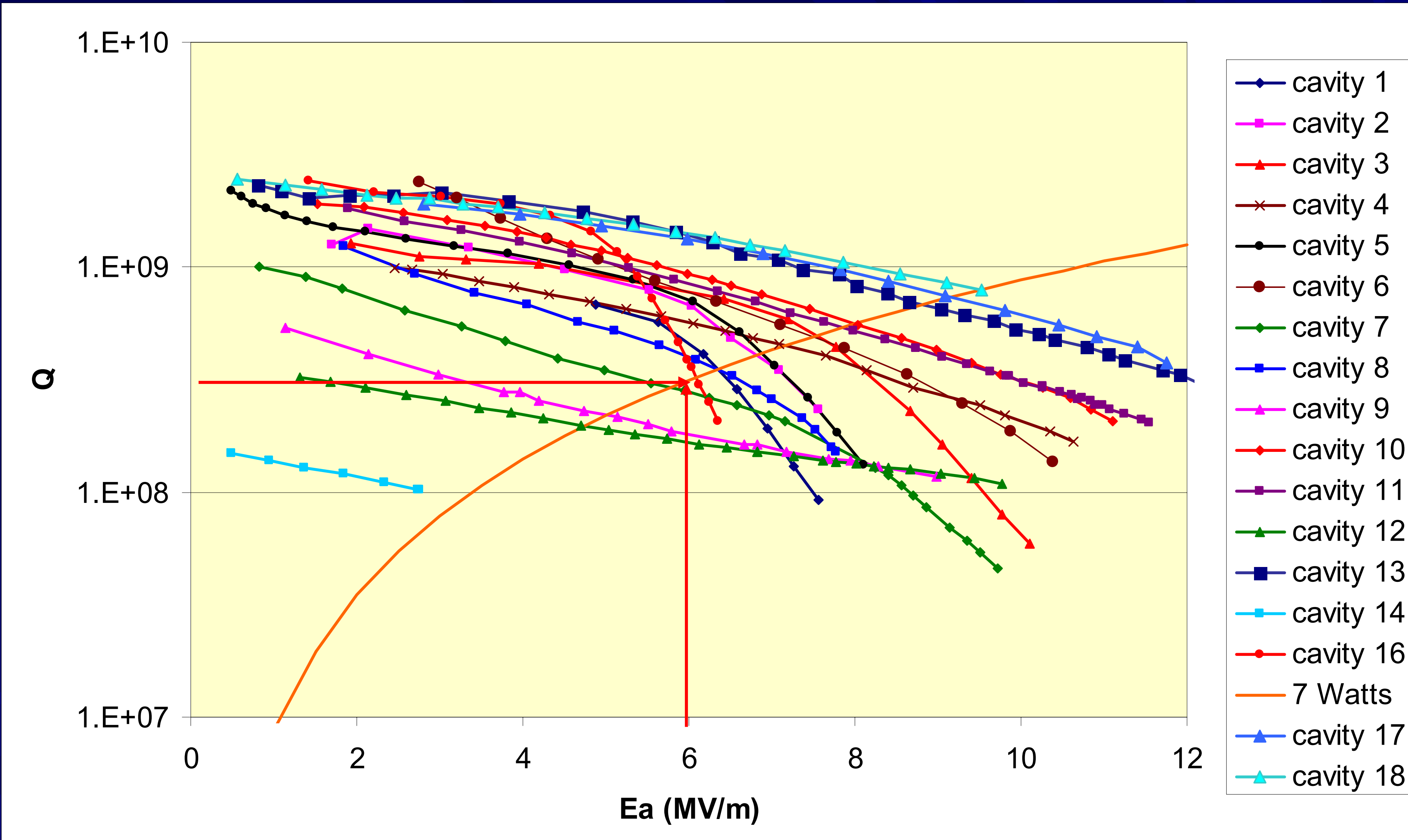
	Flat	Round
Total Number	8	13
Tested	8	11
Untested	0	2
Failed	2	2
Retested OK	2	1
Total OK	8	10



Medium Beta Section

Initial Test Results

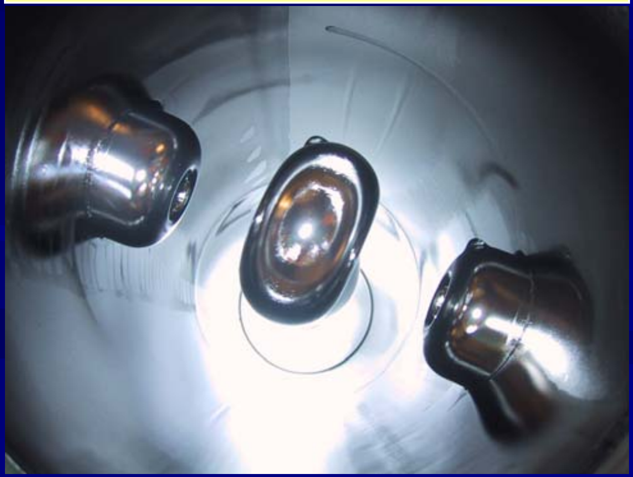
See TuP36



TRIUMF/Argonne* Collaboration – Cold Test Results

Before EP

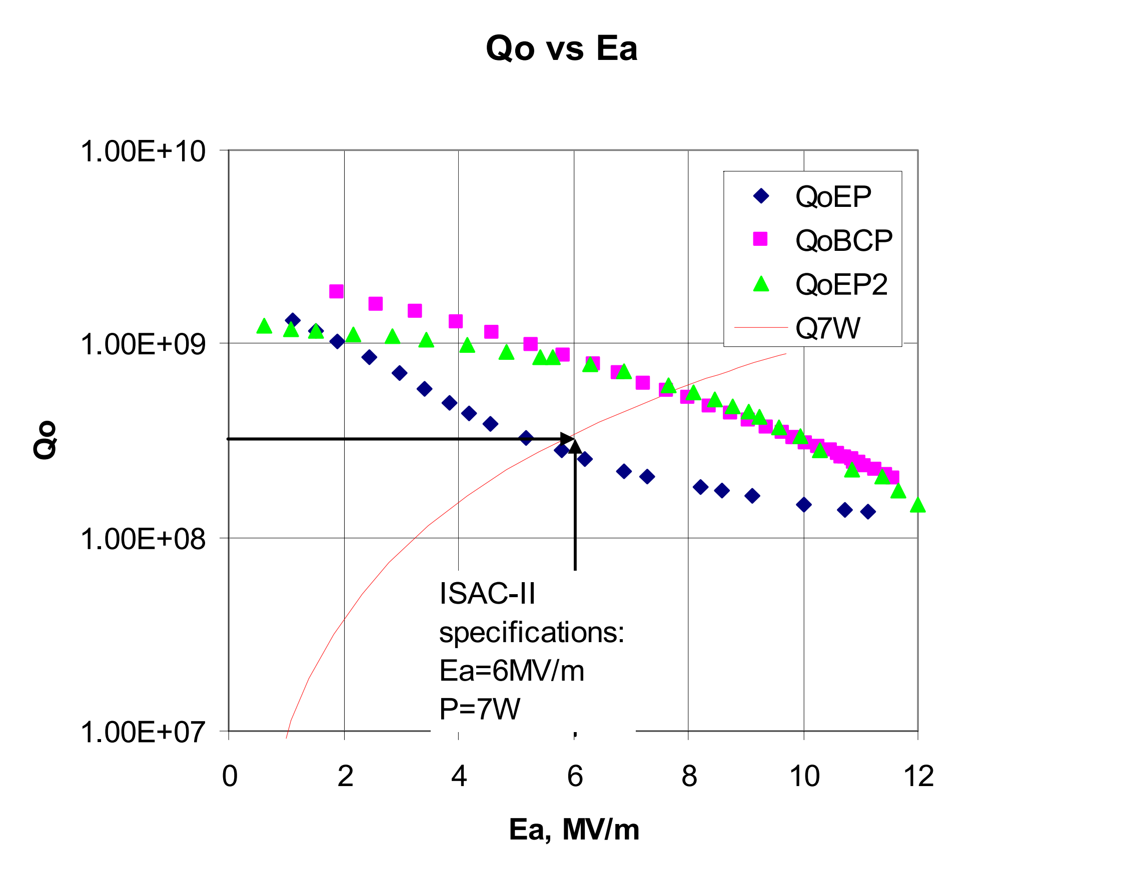
After EP



Cavity 11- BCP 130µm, EP ~65-150µm

-Yields lower Qo but less Q-slope and slightly higher Q at high gradient

- Early measurement shows effects of Q-disease



* K. Shepard, M. Kelly, M. Kedzie

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TRIUMF/Argonne* Collaboration – Cold Test Results

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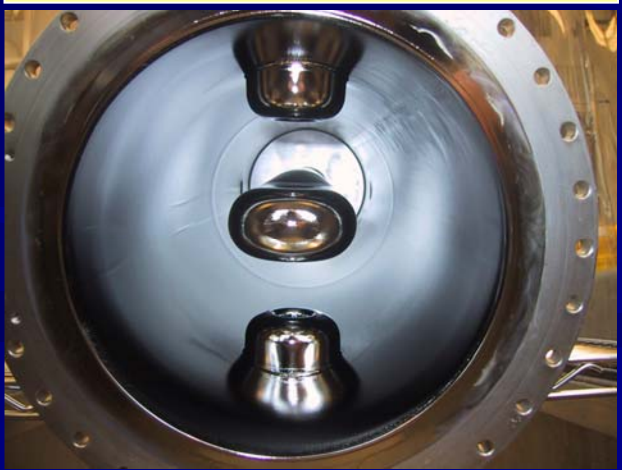
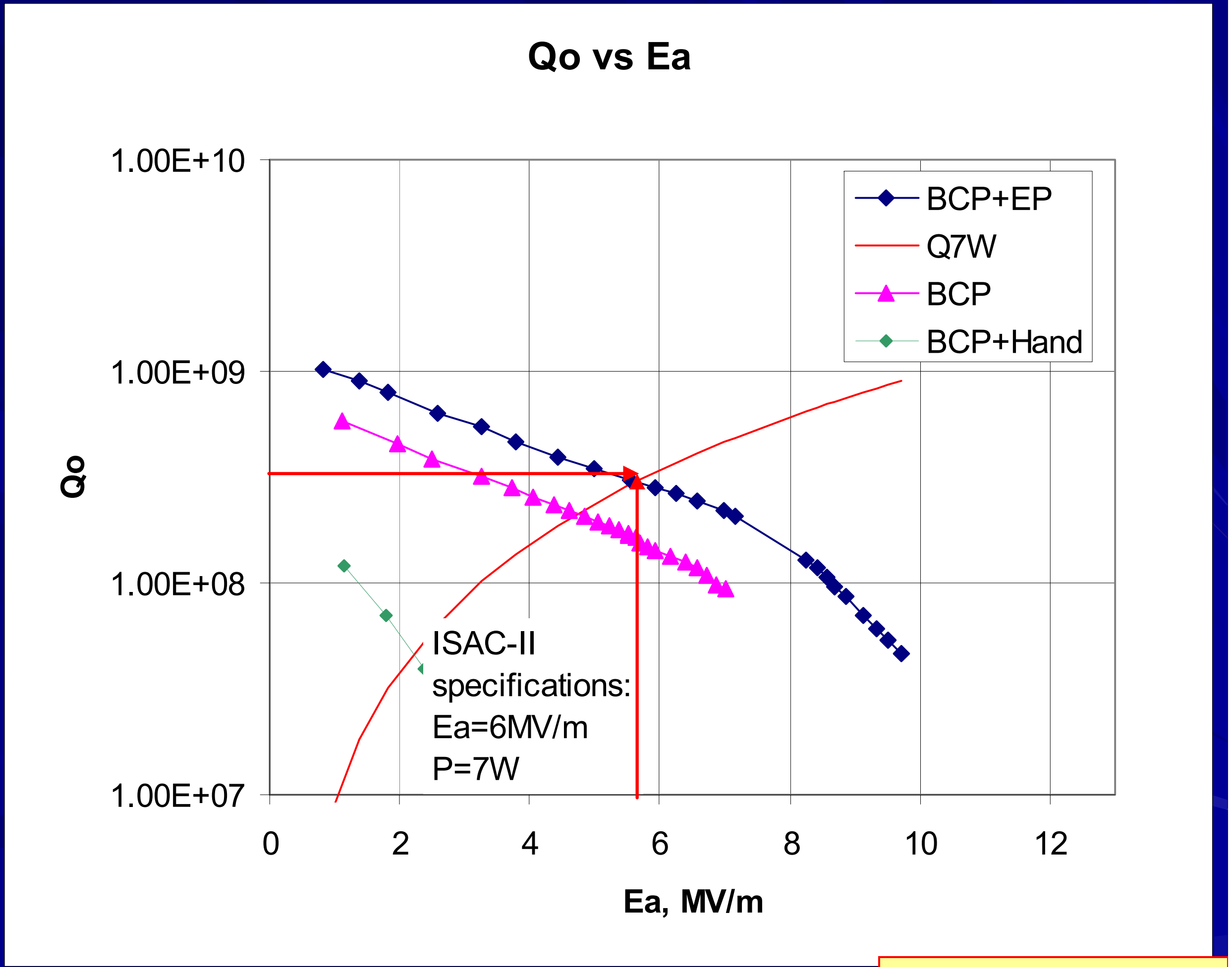


Cavity 7- BCP 130µm, EP ~25-75µm
-Provides improvement but still evidence of Q-disease



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TRIUMF/Argonne* Collaboration

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Frequency Shift for EP

- Cavity 11 Δf=+168 kHz
- Cavity 7 Δf=+110 kHz
- Simulation Results
  - Etch the top half by 100 microns
    - Δf=-179 kHz
  - Etch bottom half by 100 microns
    - Δf=+191 kHz
  - Etch 100 microns on all surfaces
    - Δf=+12 kHz

* K. Shepard, M. Kelly, M. Kedzie

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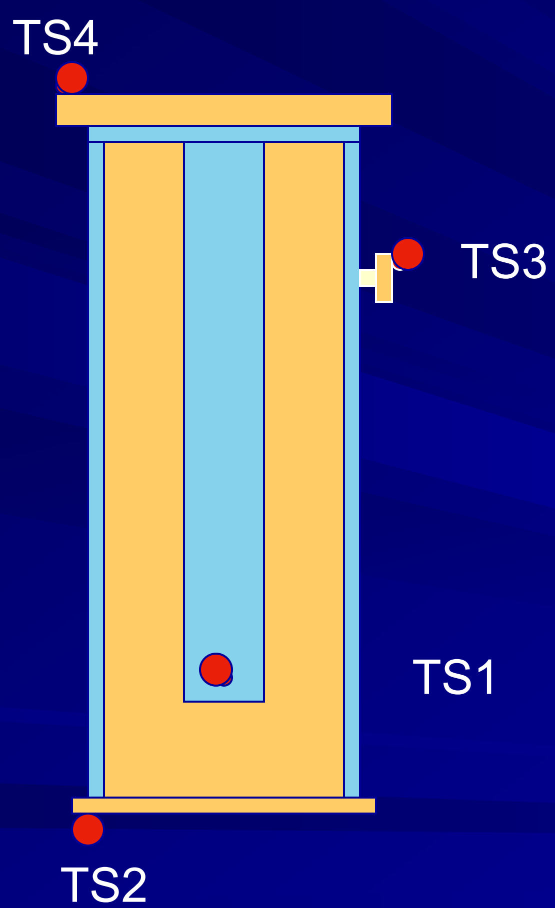
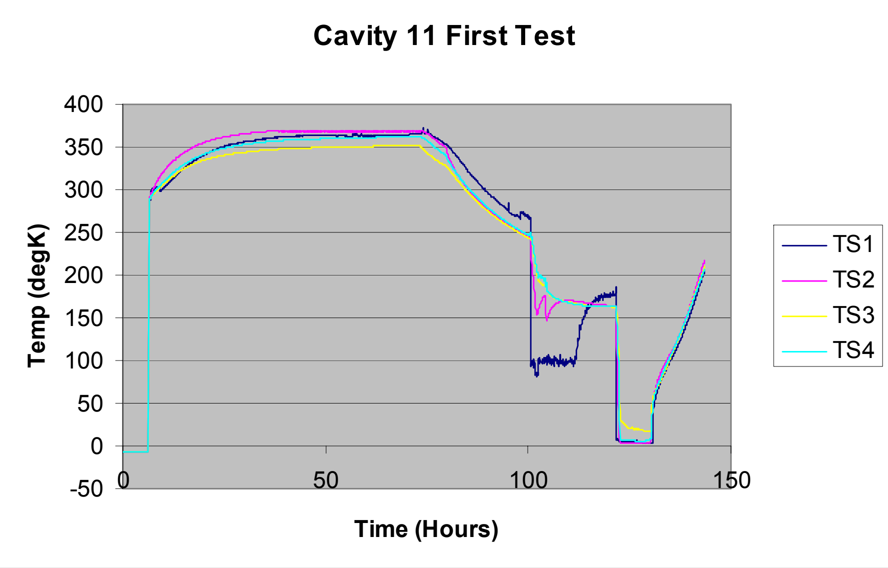
Cavity Temperature Sensors



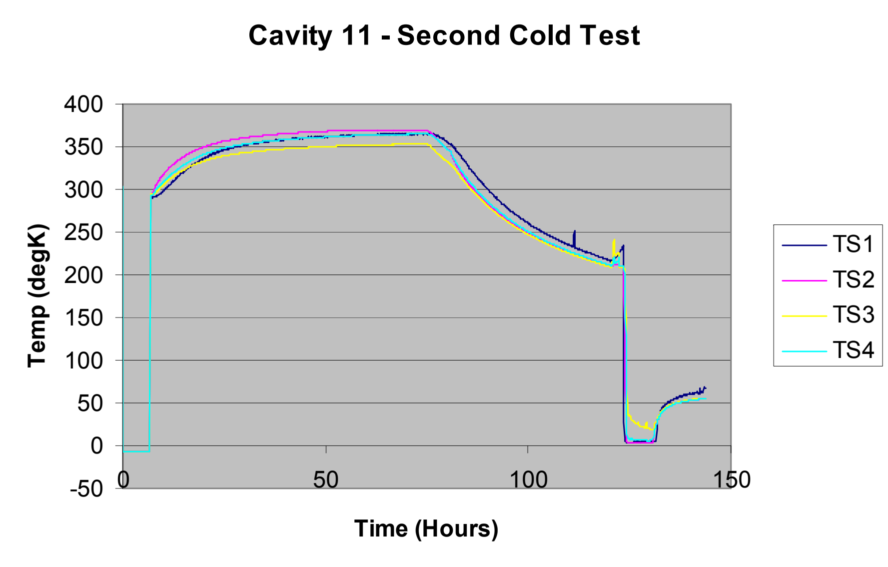
Four Temperature Sensors Installed on Cavity

- TS1 – bottom of inner conductor in helium space
- TS2 – connected to bottom flange of cavity
- TS3 - connected to coupling loop flange
- TS4- connected to top cavity flange

Cavity 11- Cool-down Rate



- Bake out at 368K for 50 hours
- LN2 pre-cool to 160K for 22 hours
  - For some part of the inner conductor was at 77K
- LHe cool from 160K to 50K in <0.7hr



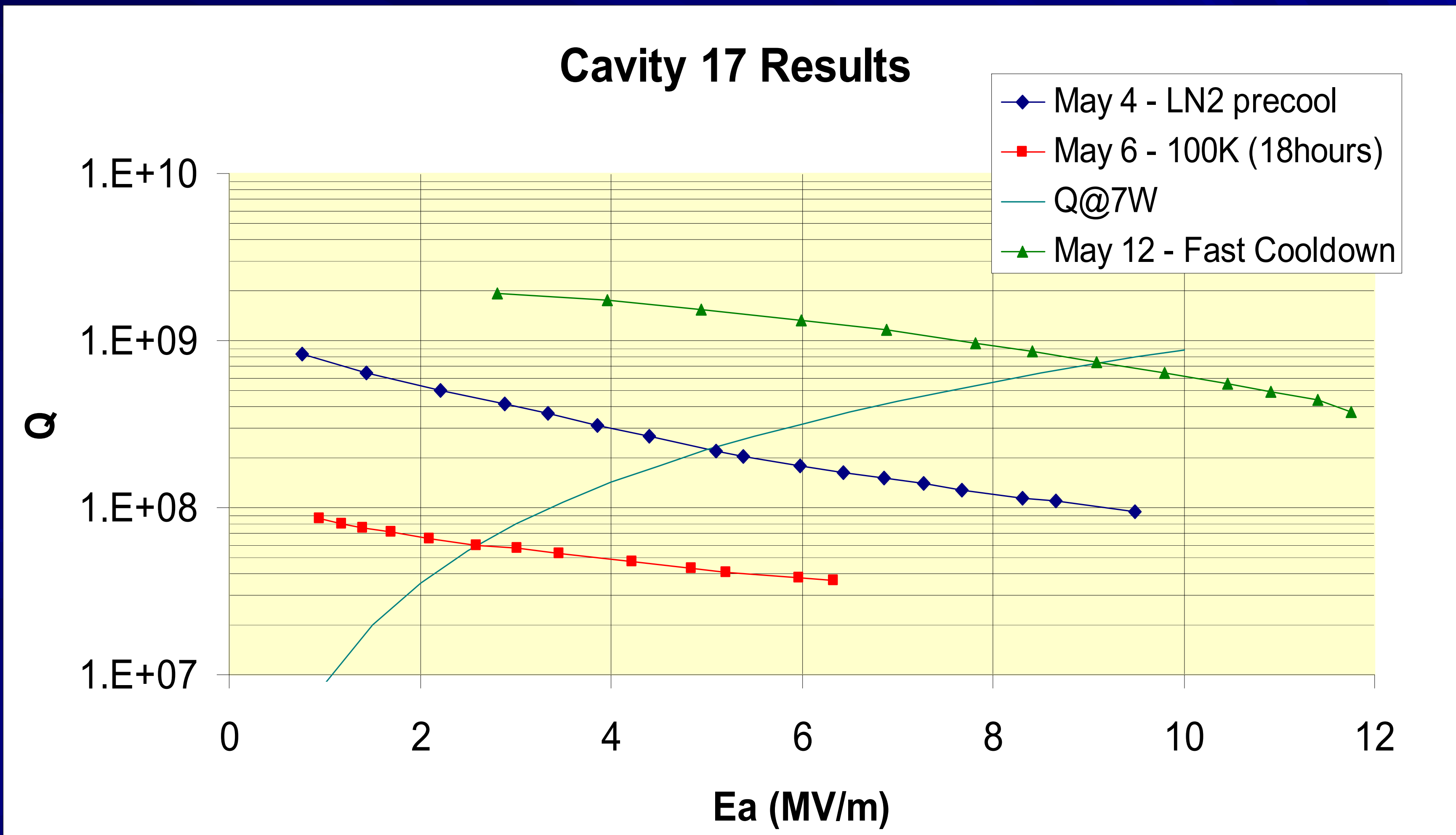
- Bake out at 368K for 50 hours
- Radiation cool from 360 to 210K in 50 hours
- LHe cool from 160K to 50K in <0.5hr

See TuP36

Q-Disease in BCP Cavities

See TuP36

- May 4 - Cavity 17 was tested after a normal cooldown with LN2 precool
- May 6 – The cavity was warmed to 100K and held for 18 hours
  - The marked Q-drop in the second test is direct evidence that cavity 17 (BCP cavity) has Q-disease.
- May 12 - The cavity was warmed up and baked at 95C for 48 hours then radiation cooled for 48 hours to 205K then fast cooled with helium to 4K



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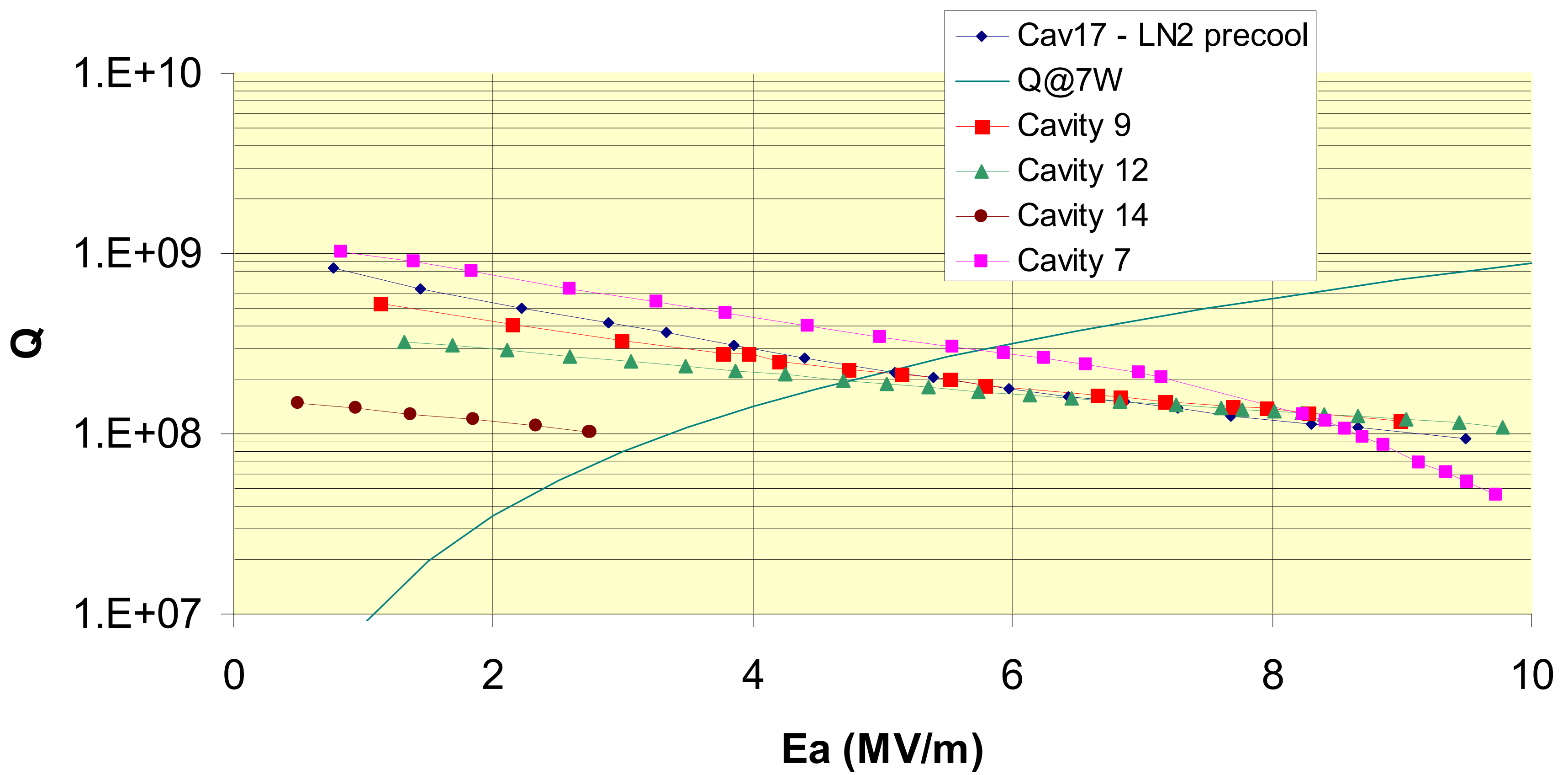
Q-Disease in Other BCP Cavities?

Are there other cavities that may have poor test results due to Q-disease?

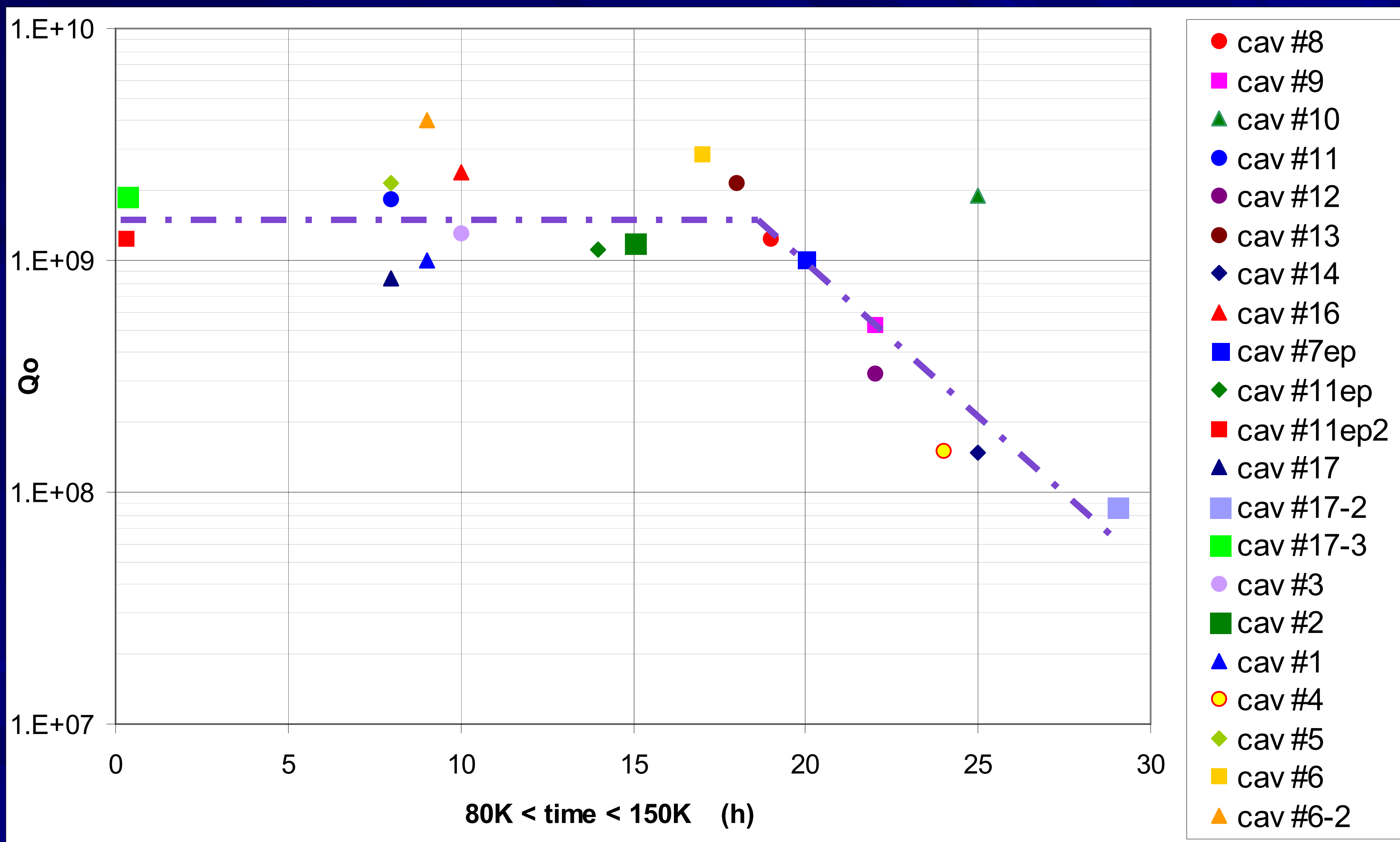
•Cavities 7(EP), 9, 12 and 14 may all be considered

•Most likely Q-disease induced during manufacture



Q-disease summary

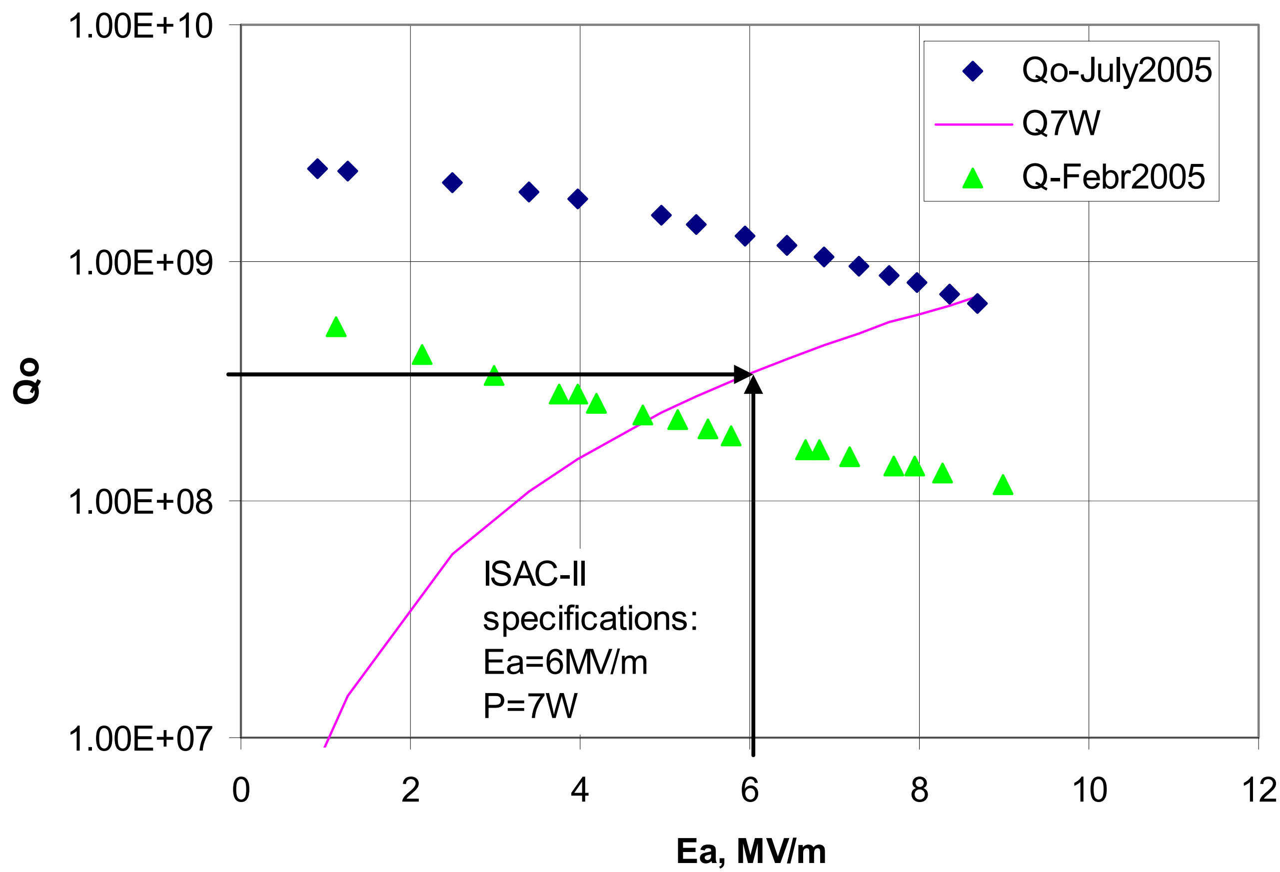
See TuP36



See TuP36

Cavity 9

- •First Test – LN2 pre-cool, evidence of Q-disease
- •Second test – no LN2 pre-cool



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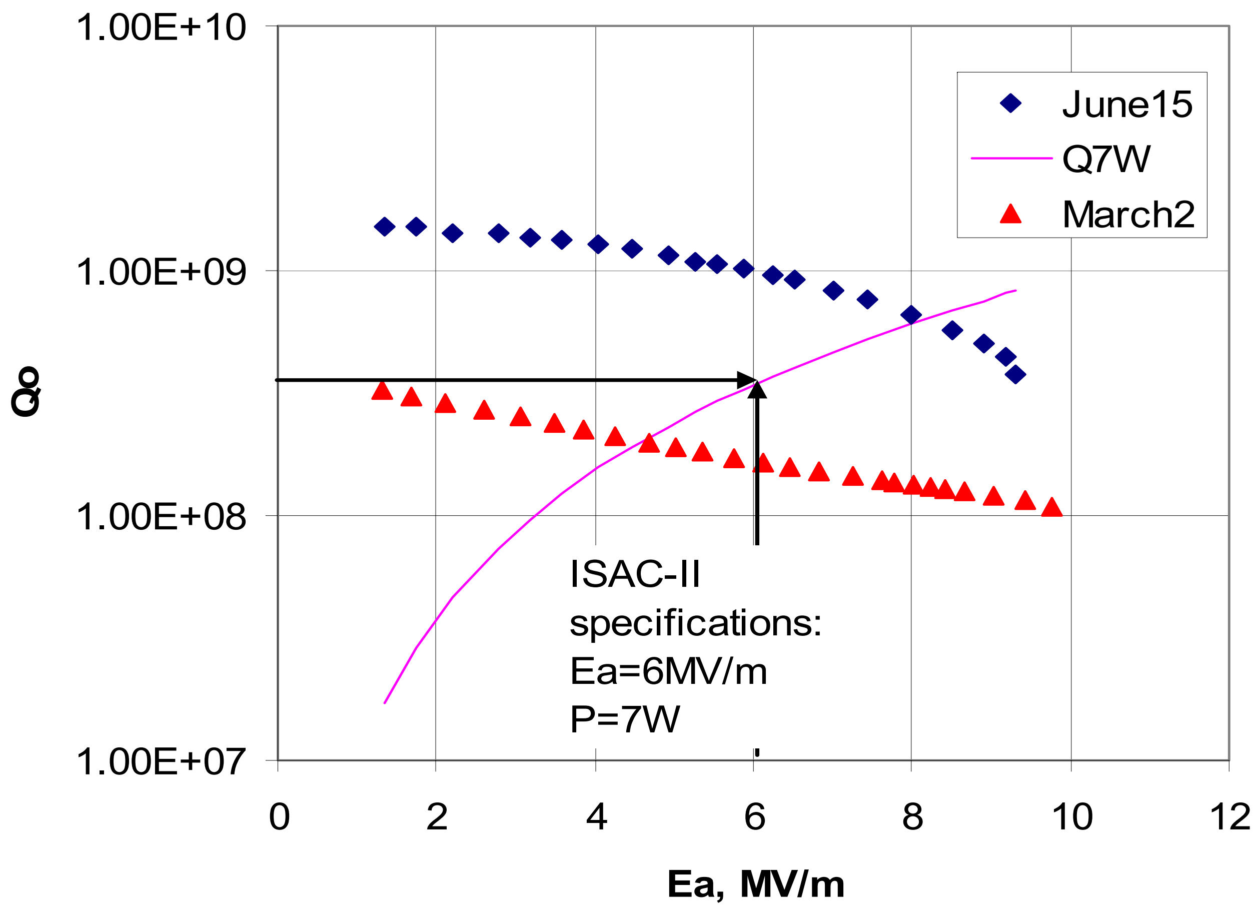
Cavity 12

•First Test – LN2 pre-cool, evidence of Q-disease

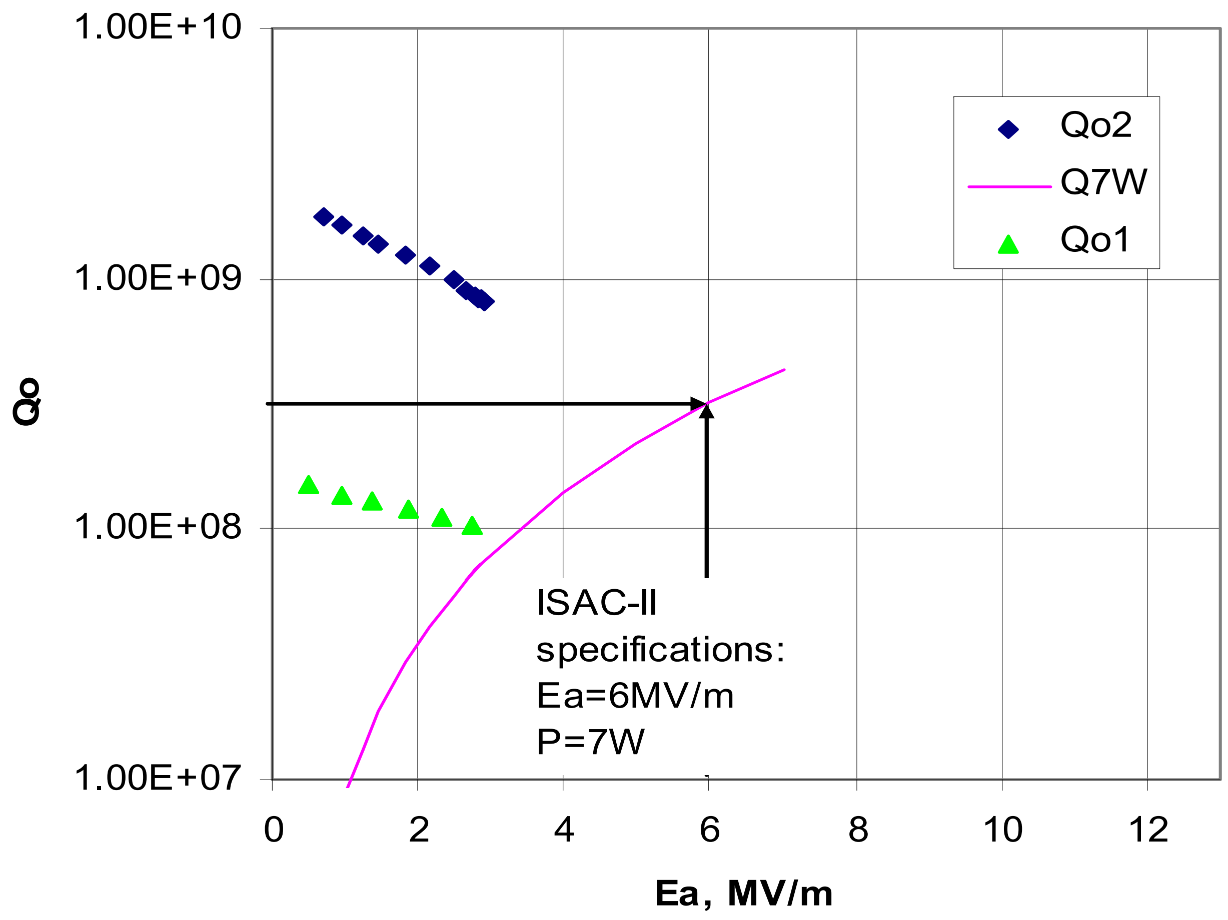
•Second test – no LN2 pre-cool



See TuP36

Cavity 14

- First Test – LN2 pre-cool, evidence of Q-disease
- Second test – no LN2 pre-cool, hard Quench at 3MV/m



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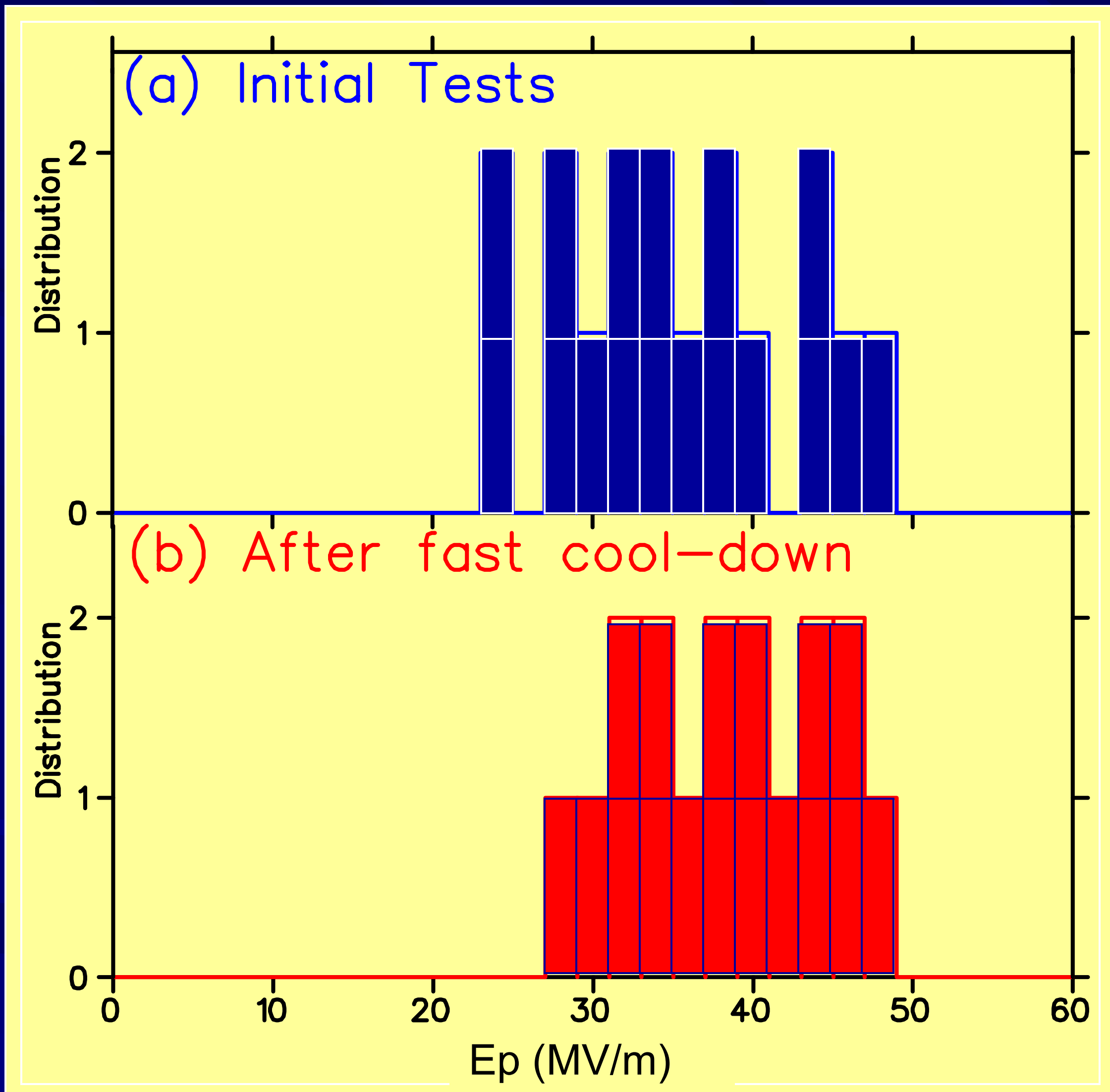
Cavity Performance Statistics – 17 cavities

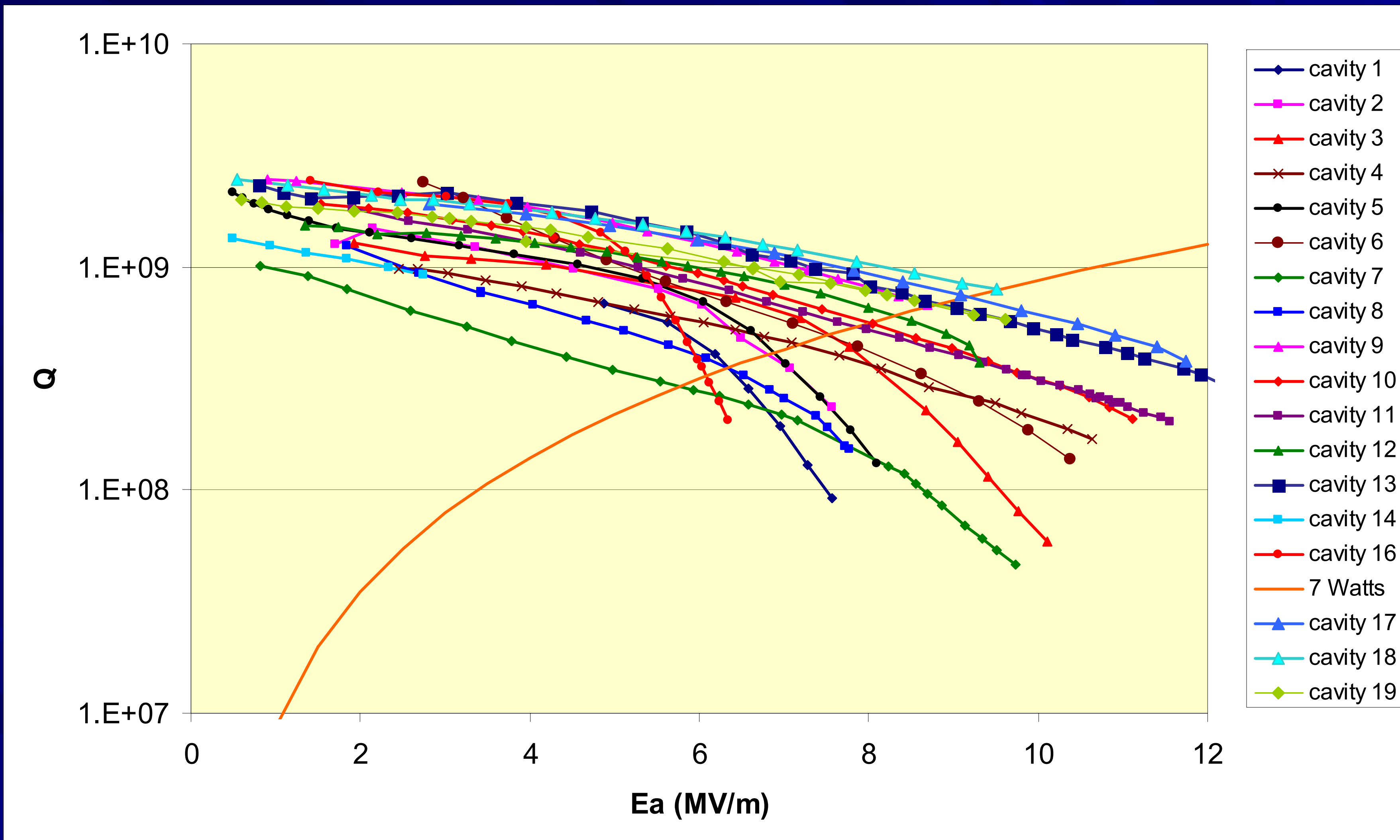


Distribution of peak surface field at P_{cav}=7W

- Three cavities show signs of Q-disease from LN2 pre-cooling
- These cavities were retested with fast cooldown
- Average peak surface field at operating power is now 38MV/m corresponding to a voltage gain of 1.4MV/cavity

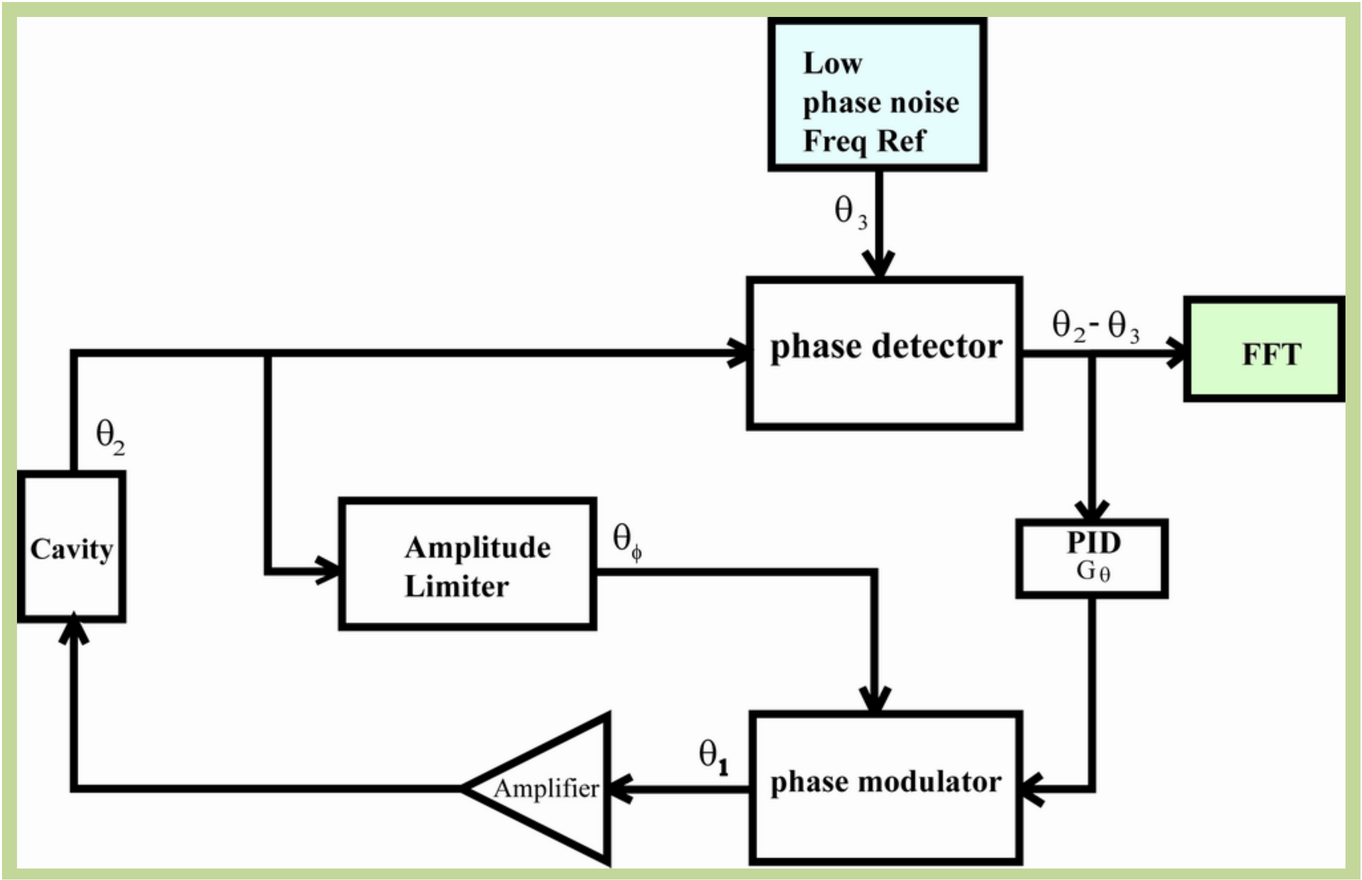
See TuP36

Latest Summary

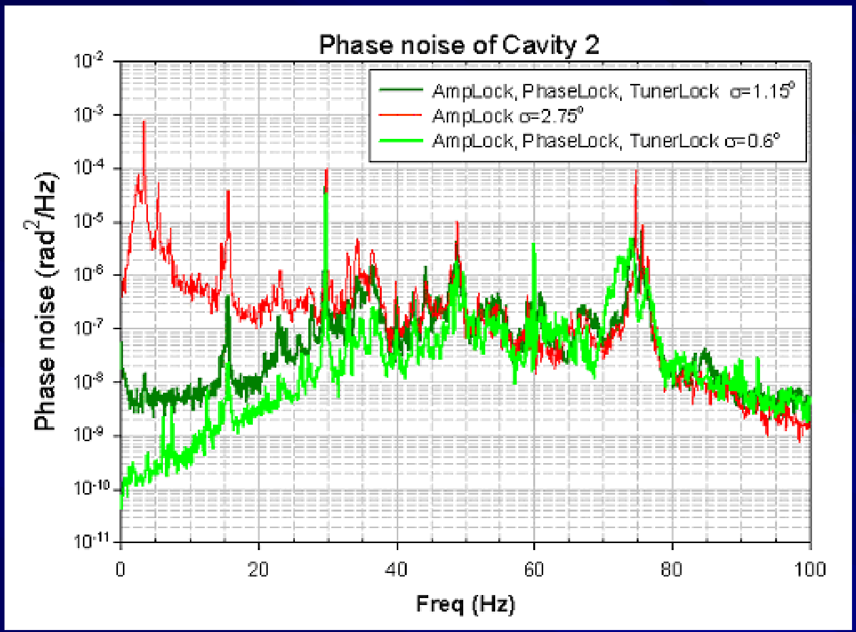


Phase Noise Diagnostic

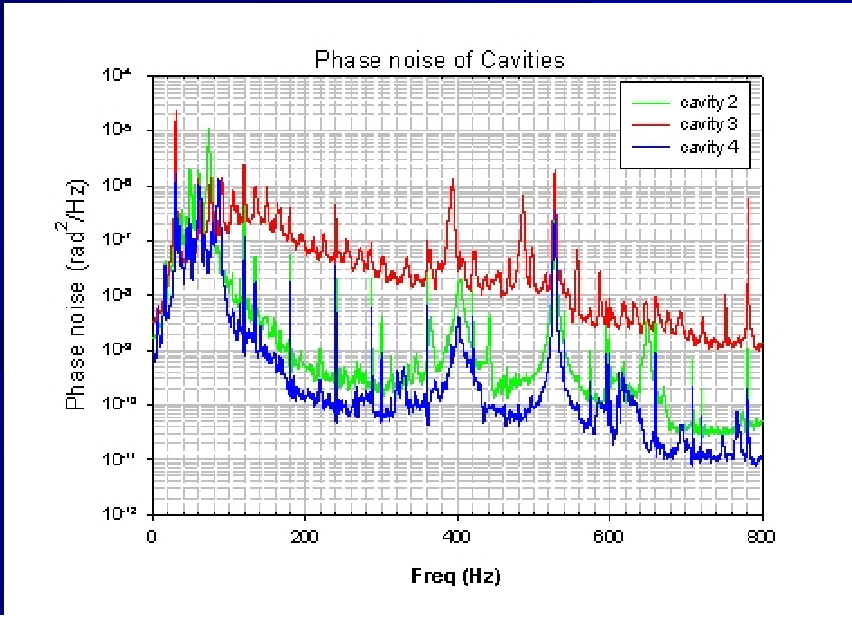
- Add a low noise frequency synthesizer and FFT analyzer to self-excited regulation system
- Set loop gain G_θ to minimum to keep phase detector in the linear range



Phase Noise Measurements



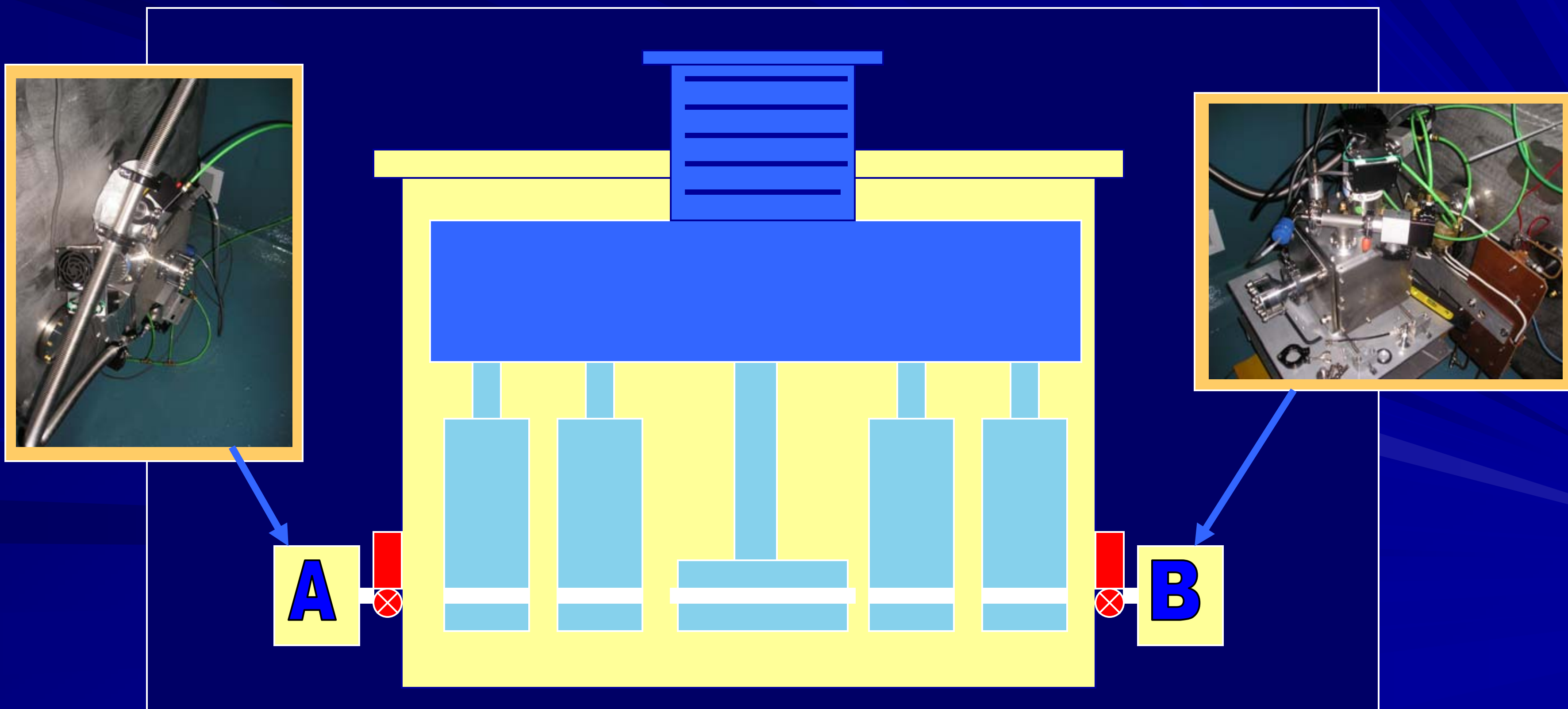
- Here the sampled spectra show the suppression of phase noise below the regulation bandwidth when the phase loop is closed.
- resonance peaks can help diagnose system
    - 74 Hz – lowest cavity mode
    - 48 Hz – mechanical fan in rf amplifier
    - 3 Hz – cavitation boiling of LHe



- Wider scans of the phase noise spectra for different cavities reveal other resonance modes as well as defects in the power amplifier of Cavity #3.

Alpha Particle Acceleration

- ISAC-II test cryomodule is outfitted with diagnostic boxes for and aft separated from the main vacuum space by gate valves.
- Upstream box A contains ^{244}Cm alpha source (5.8MeV but degraded by containment foil to 2.8MeV)
- Downstream box B contains silicon detector for energy measurement

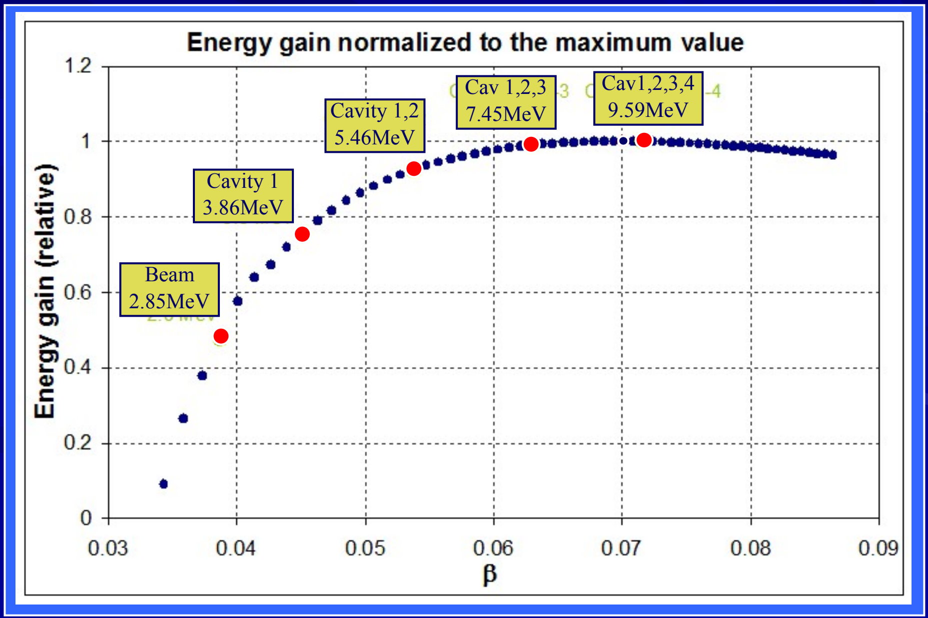


Expected Energy Gain

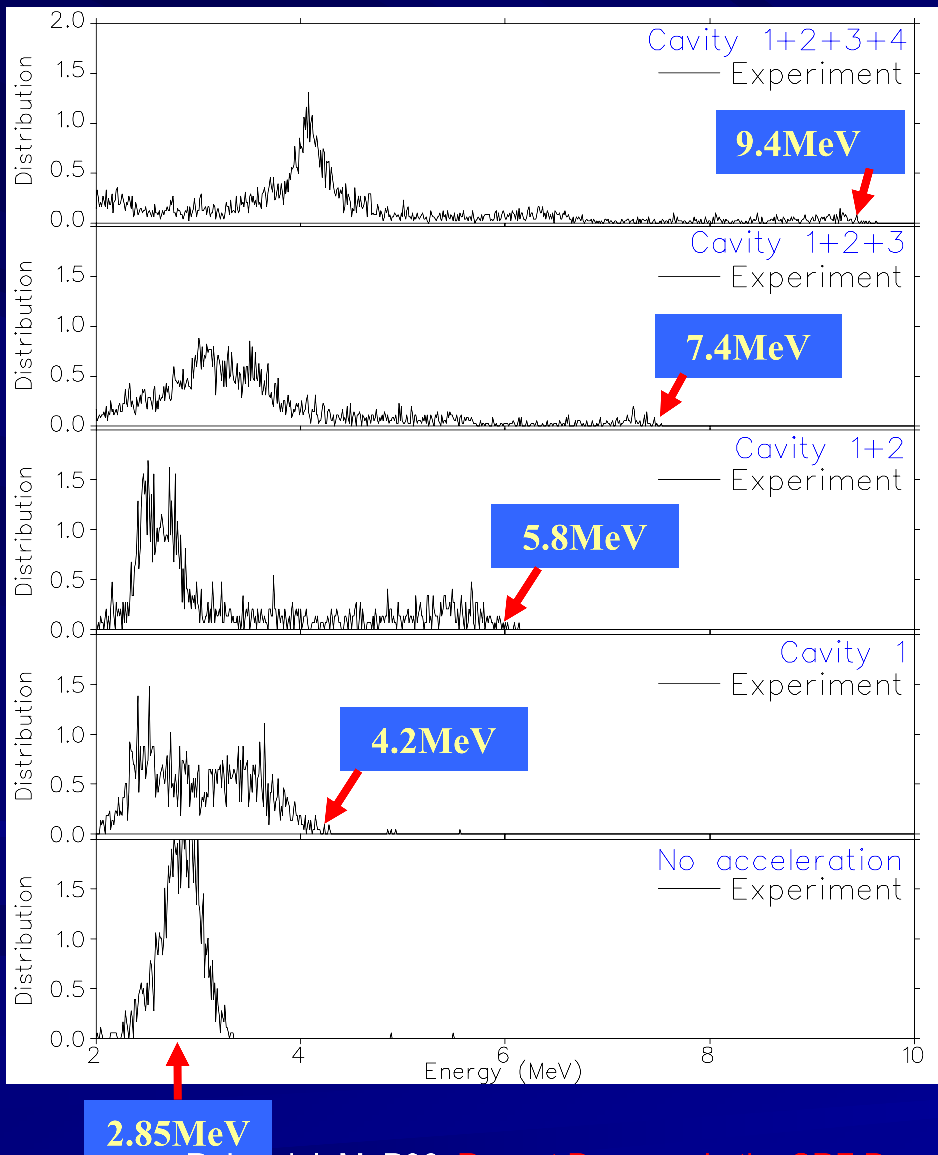
Medium Beta Cavities

- 6 MV/m, L_{eff}=0.18m, Pcav=4W
- E_{peak}=30MV/m, B_{peak}=60μT
- ΔV=1.08MV, β_0=0.07
- α-particles A/q=2

Cavity	E (MeV)	TTF/TTF_0	ΔE (MeV)
Off	2.85	0.47	1.01
1	3.86	0.74	1.60
1,2	5.46	0.92	1.99
1,2,3	7.45	0.99	2.14
1,2,3,4	9.59	-	-



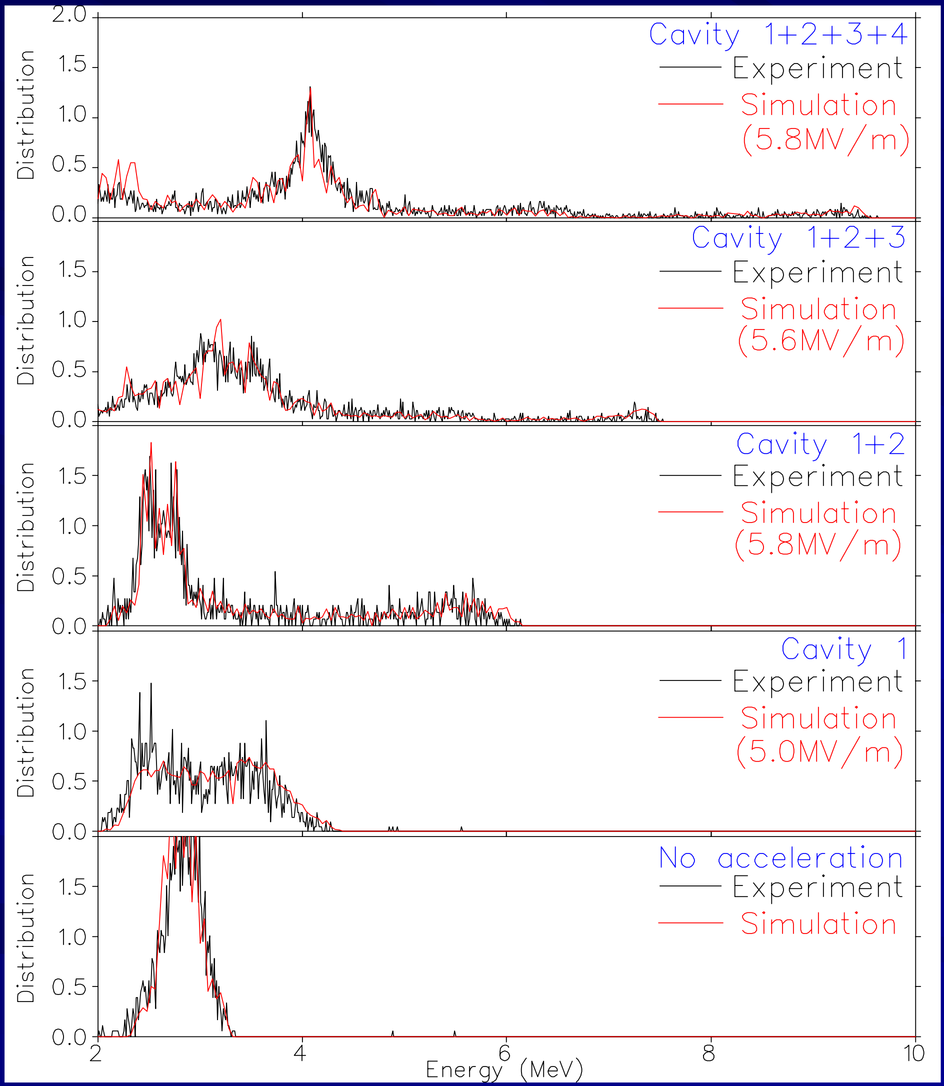
Test Results



- Cavities set for Ea=6MV/m and phase optimized for maximum acceleration
    - Scan phase every 30deg and count for 10 minutes to collect spectra
- Broad final energy spectra due to unbunched, uncollimated beam with large initial energy spread

Cavity	E (MeV)	Etest (MeV)
Off	2.85	?
1	3.86	4.2
1,2	5.46	5.8
1,2,3	7.45	7.4
1,2,3,4	9.59	9.4

Alpha Spectra Fitting

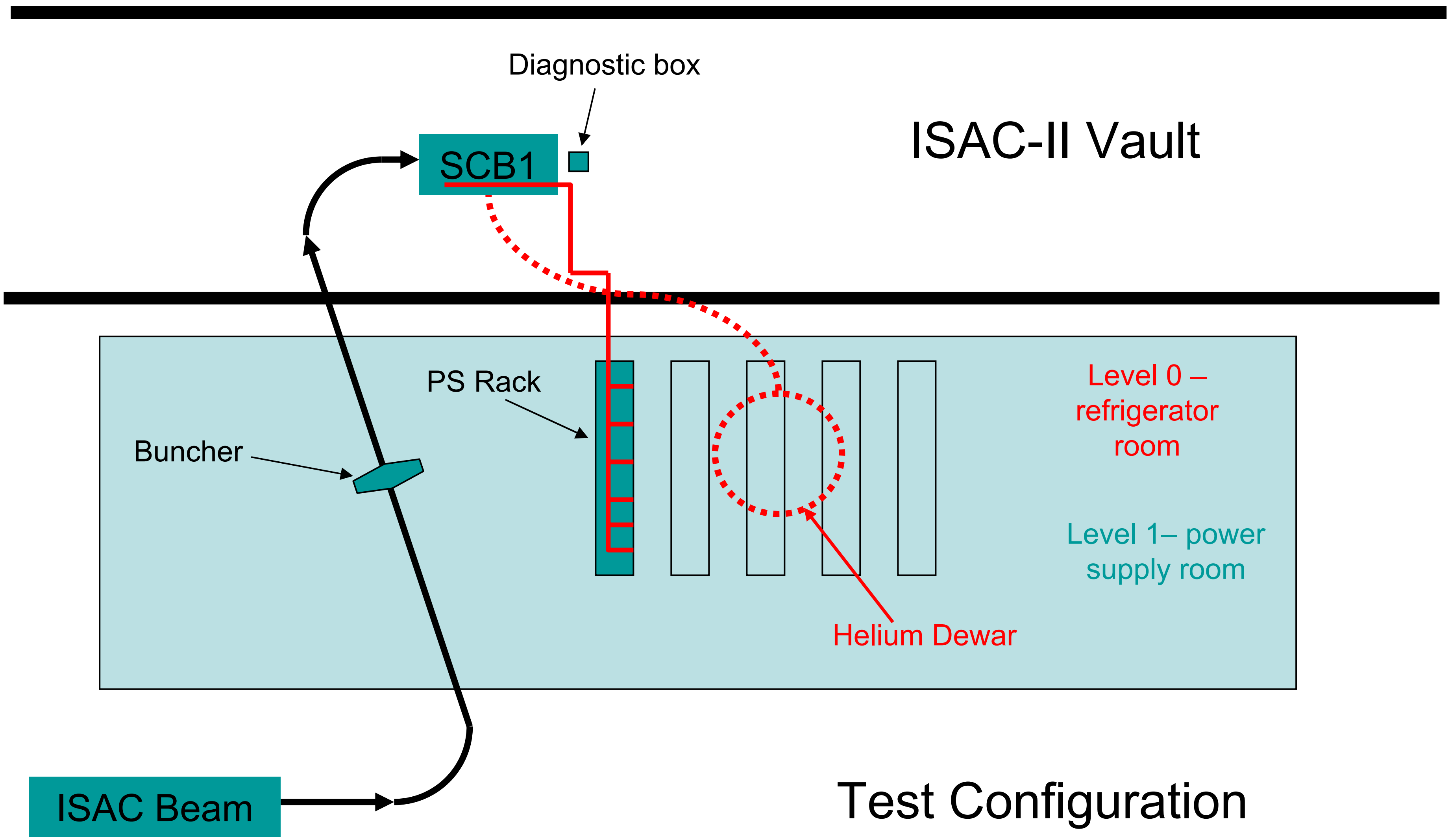


- Beam simulation code LANA was used to model the alpha source and cryomodule acceleration
- Cavity phase and amplitude were varied to obtain the best fit to the data
- Cavity settings produce a unique spectral fingerprint so that V and φ can be determined unambiguously
- This method gives the following gradients

Cavity	1	2	3	4
Gradient (MV/m)	5.0	5.8	5.6	5.8

- Average Ea=5.6MV/m within 6% of goal.

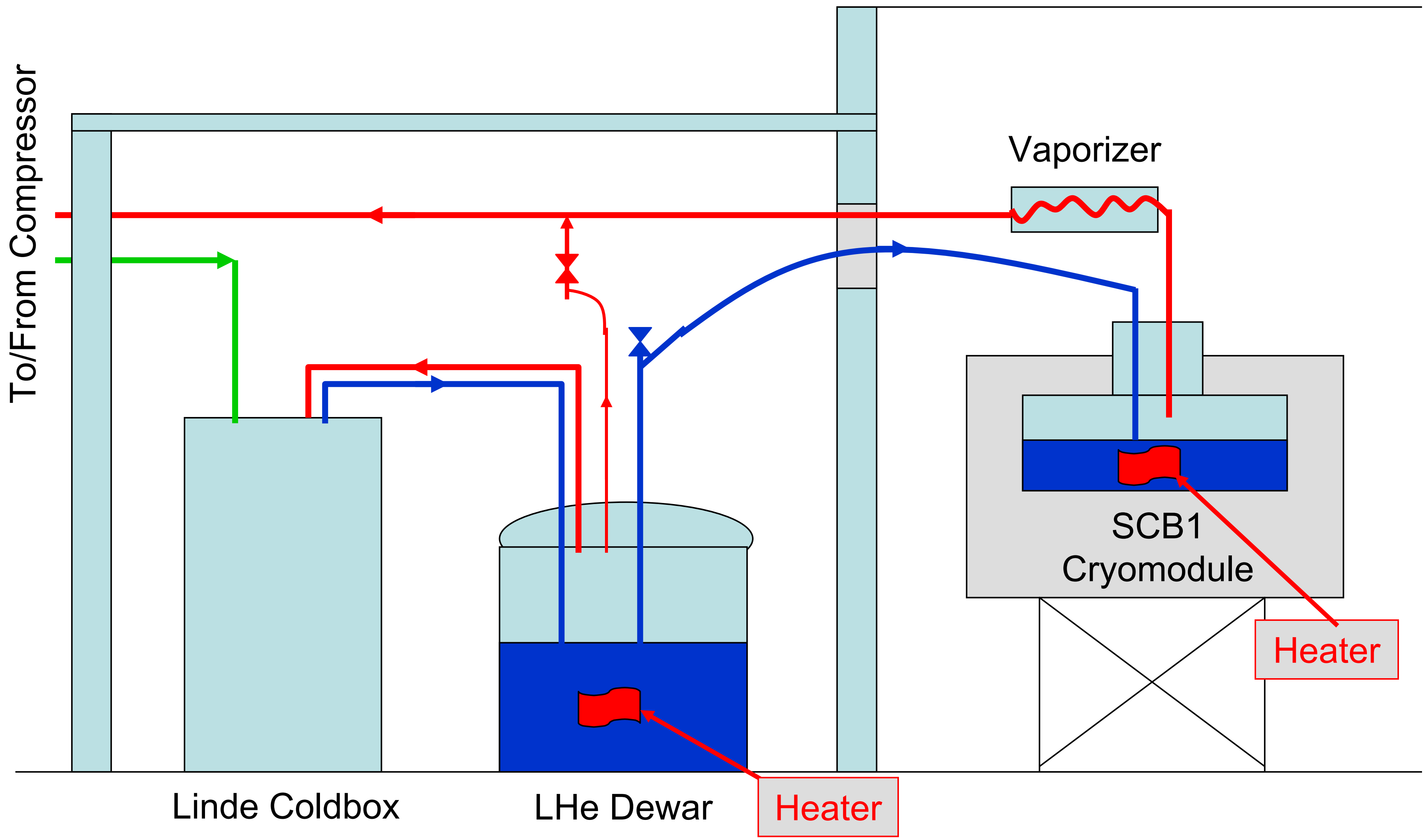
SCB1 Vault Test



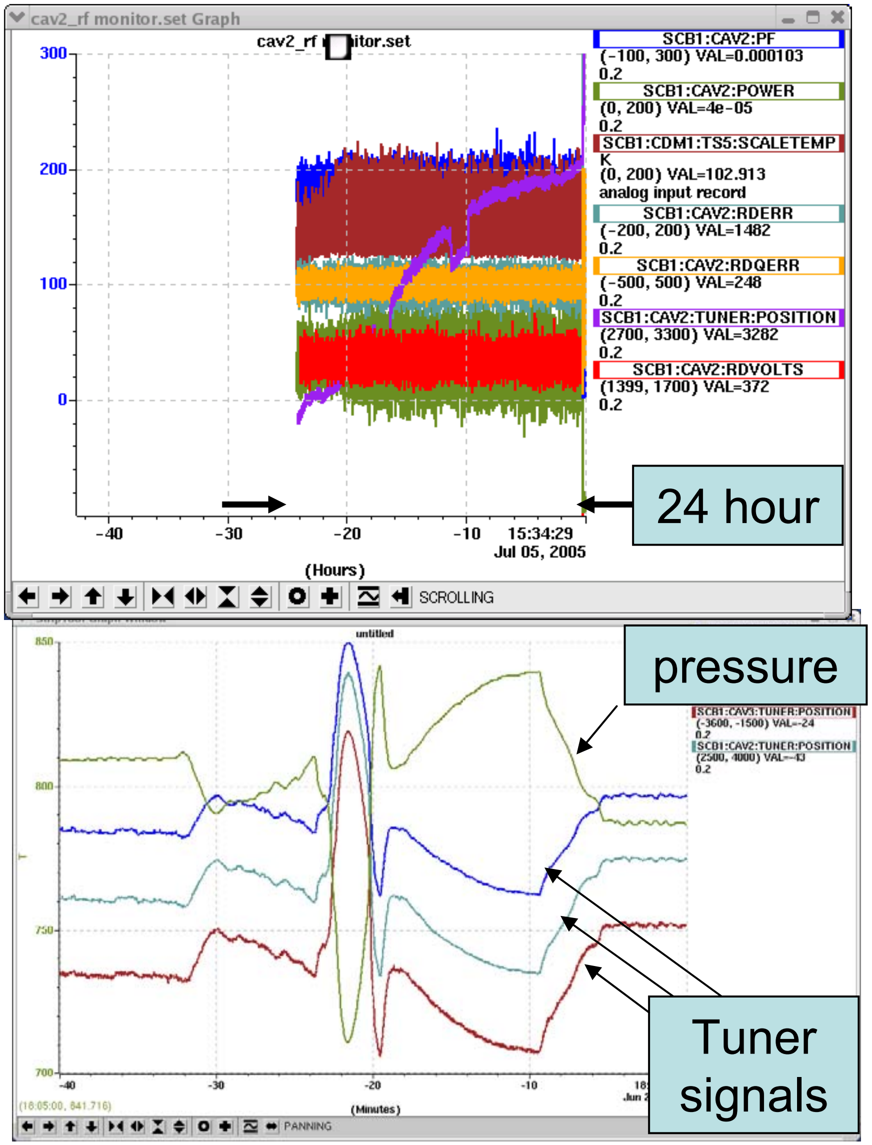
Goals

- S-bend commissioning
- First operation of refrigerator by TRIUMF personnel
- Test services/cabling performance from final location
  - Identify cross-talk or environmental problems
- Test rf performance with refrigerator in continuous delivery
- accelerate some beam

Helium Flow Schematic



RF Operation



- Three cavities locked at ISAC-II specification
  - Ep=30MV/m, 106.08MHz, P_{for}=200W
  - Cavity 1 has an in-vacuum open circuit in the rf power feed
- 24 hour test at ISAC-II specifications completed successfully
  - Refrigerator run in continuous feed cycle
- Frequency tuners effectively track rf frequency to maintain lock over a large pressure variation in the helium space

Acceleration – July 7

- Injected $^{26}Mg^{6+}$ from ISAC at 1.5MeV/u into SCB1
- Measured final energy with Si detector
- Achieved 3.5MV acceleration from three cavities
  - Corresponds to average values of Ep=33.4MV/m, Bp=67mT (Ea= 6.7MV/m)
  - Coupling beta 200, Pf=310W, Pcav=6W
  - One cavity not operational