Overview of Cavity Performance World Wide

High Energy Accelerator Research Organization (KEK), Accelerator Lab

Kenji Saito

Scope of my Talk

- Roughly speaking, to date, main flow of SRF cavity application is for the SRF electron Linacs (ERL, ILC…) and the SRF high power proton Linacs(SNS upgrade, J-parc upgrade, Project X…). Due to the tight time limitation, I will pick up only the medium β to β=1 machines with multi-cell cavities.

- I will take Jlab example for a scenario to see how nicely the understandings in SRF physics and the cure techniques are feed-backed to projects, and the SRF cavity performance has been pushed up very much in this decade.

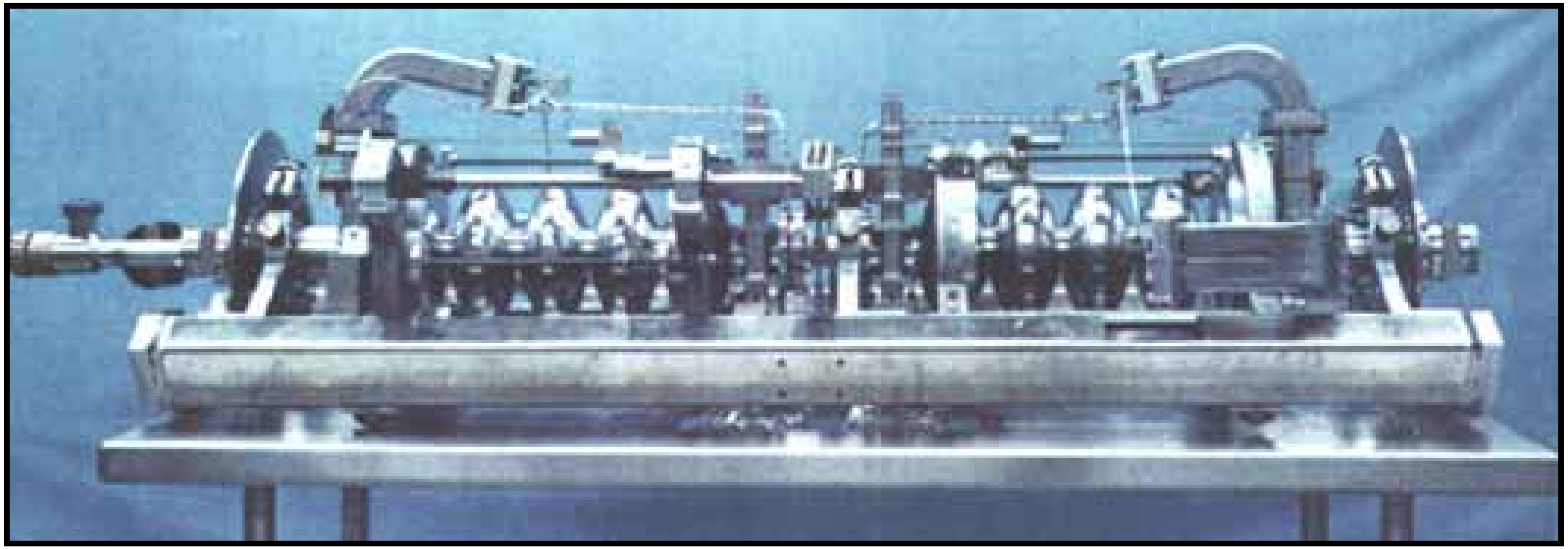
- Through surveying cavity performance in the past and present SRF accelerators, you will have a bright scope for future applications.

New technology feed-back to Projects (Picked up Multi-cell application only)

Cure technology for performance limitation	Cure	1980	1985	1990	1995	2000	2005	2010		2015
			TRISTAN	HERA, CEBAF, LEP-II		TTF, SNS	FLASH	Jlab 12GeV	XFEL, STF, Cornell ERL	ILC, Project X
1) BCP				○	○	○		○	○	
2) Annealing	HQD		○			○	○	○	○	○
3) Spherical Shape	MP		○	○	○	○	○	○	○	○
4) High Pure Water	FE		○	○	○	○	○	○	○	○
5) Clean Room Assembly	FE		○	○	○	○	○	○	○	○
6) T-mapping System	TI,FE,HFQS		○	○	○	○	○	○	○	○
7) EP+Baking	HFQS		○				○	○	○	○
8) High RRR Nb(RRR>250)	TI			○		○	○	○	○	○
9) Nb Film Coating	Cost				○					
10) HPR	FE					○	○	○	○	○
11) CBP/Tumbling	TI									
12) Low Loss shape	CMF							○		
13) LG Nb Material	Cost									
14) Dry-ice Cleaning	FE									
15) Post EP Cleaning	FE							○		○
16) Slow Evacuation	FE							○		
17) Clean Annealing	HFQS									
Eacc,max[MV/m] in QA test			10	8/18	10	25	28-40	43	25-40	25-40
Operation Gradient [MV/m]			5	5	5	15-20	20-25	20	23/31.5/15	31.5
Comments MP:Multipacting FE: Field Emission FEN:Field Enhancement HFQS: High Field Q-Slope TI: Thermal Instability CM:Critical Magnetic Field Cost: Cost down			508MHz, 4.2K	500MHz, 4.2K	1.5GHz, 2K	1.3GHz, 2K, 2.1K(SNS)	1.3GHz, 2K	1.5GHz, 2K Pre-production phase	1.3GHz, 2K Pre-production phase	1.3GHz, 2K Under developing

CEBAF Cavity at JLAB

RF parameters	CEBAF
f_o[MHz]	1497.0
k_{CC}[%]	3.29
Ep/Eacc	2.56
Hp/Eacc [mT/(MV/m)]	4.56
R/G [Ω]	96.5
Design performance	Eacc>5MV/m, Qo>2.4E+9



Paired 1.5GHz, 5-Cell cavities (4paires in a horizontal cryomodule)

Cavity performance of the CEBAF

by C.Reece et al., PAC1993

High RRR material+BCP+Clean handling, but No HPR

Usable performance
6MV/m, Qo=5E+9

1GeV/turn

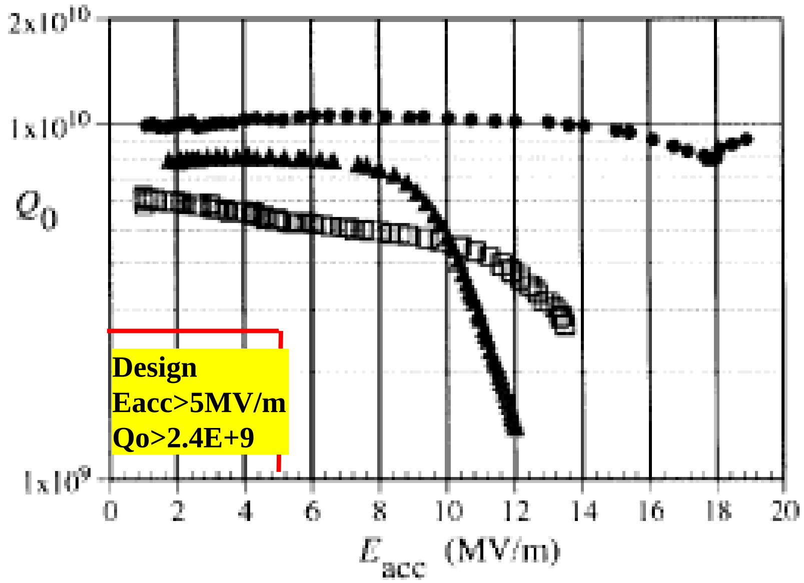
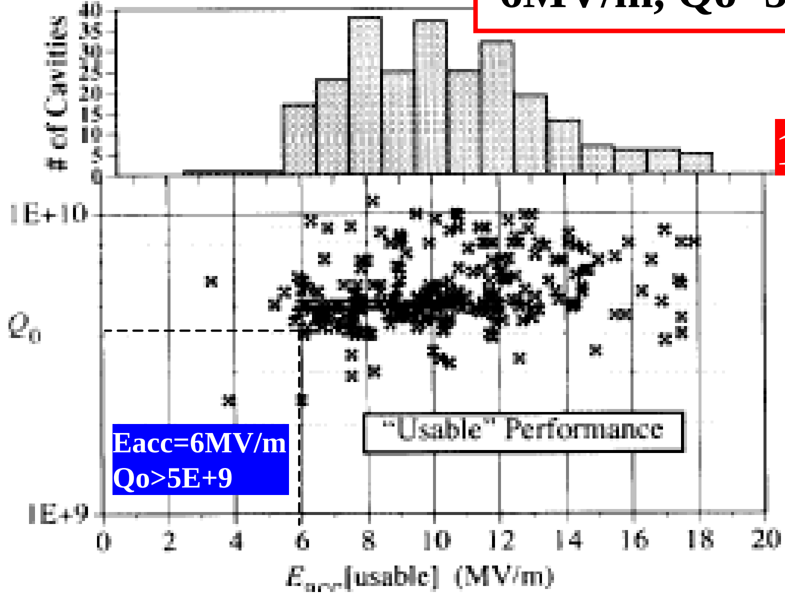


Figure 1. Typical cavity performance in vertical testing.



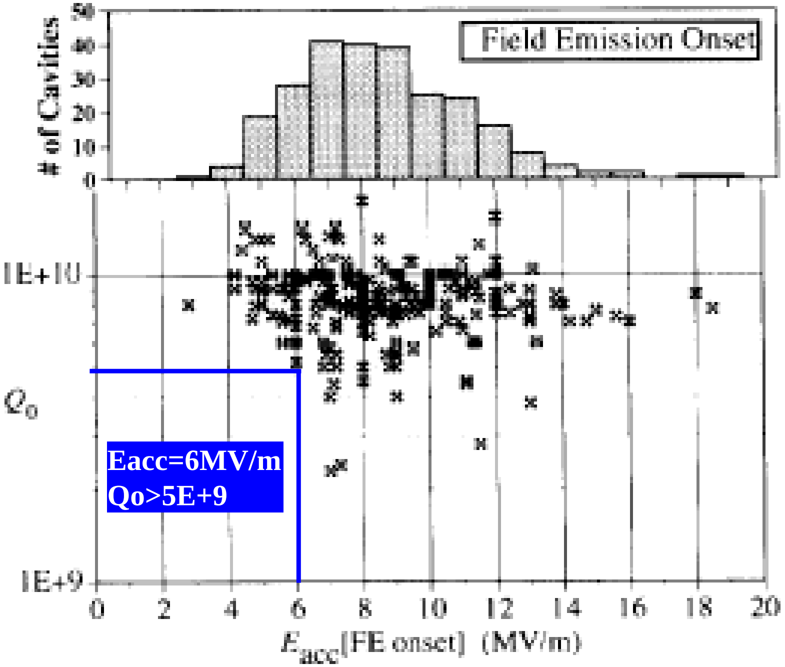


Figure 3. Q and gradient at onset of field emission loading.

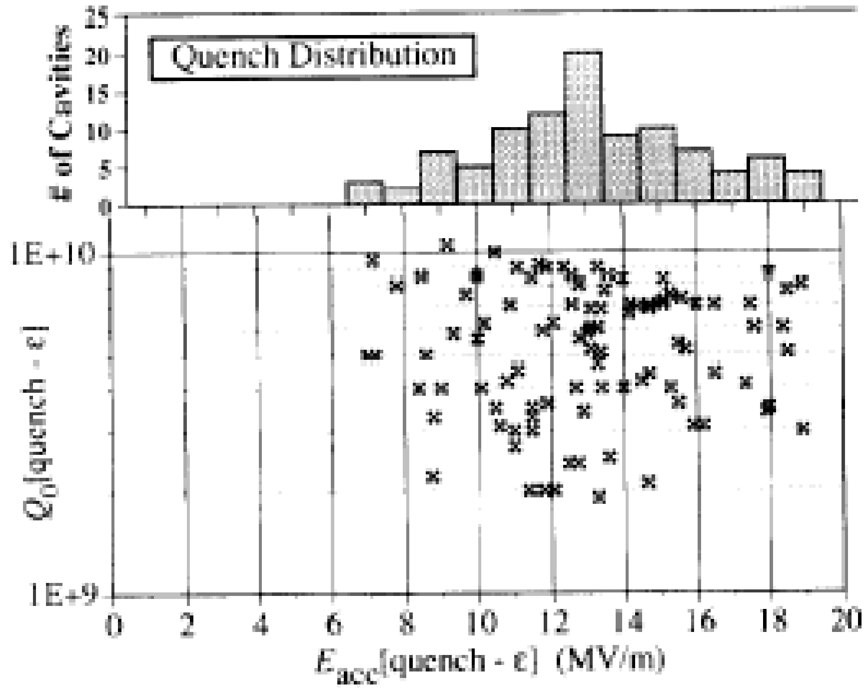
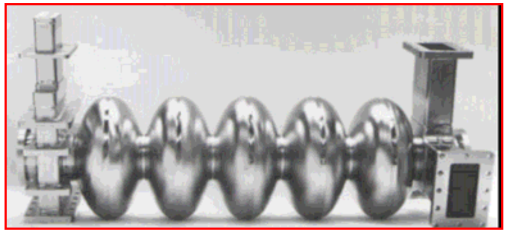
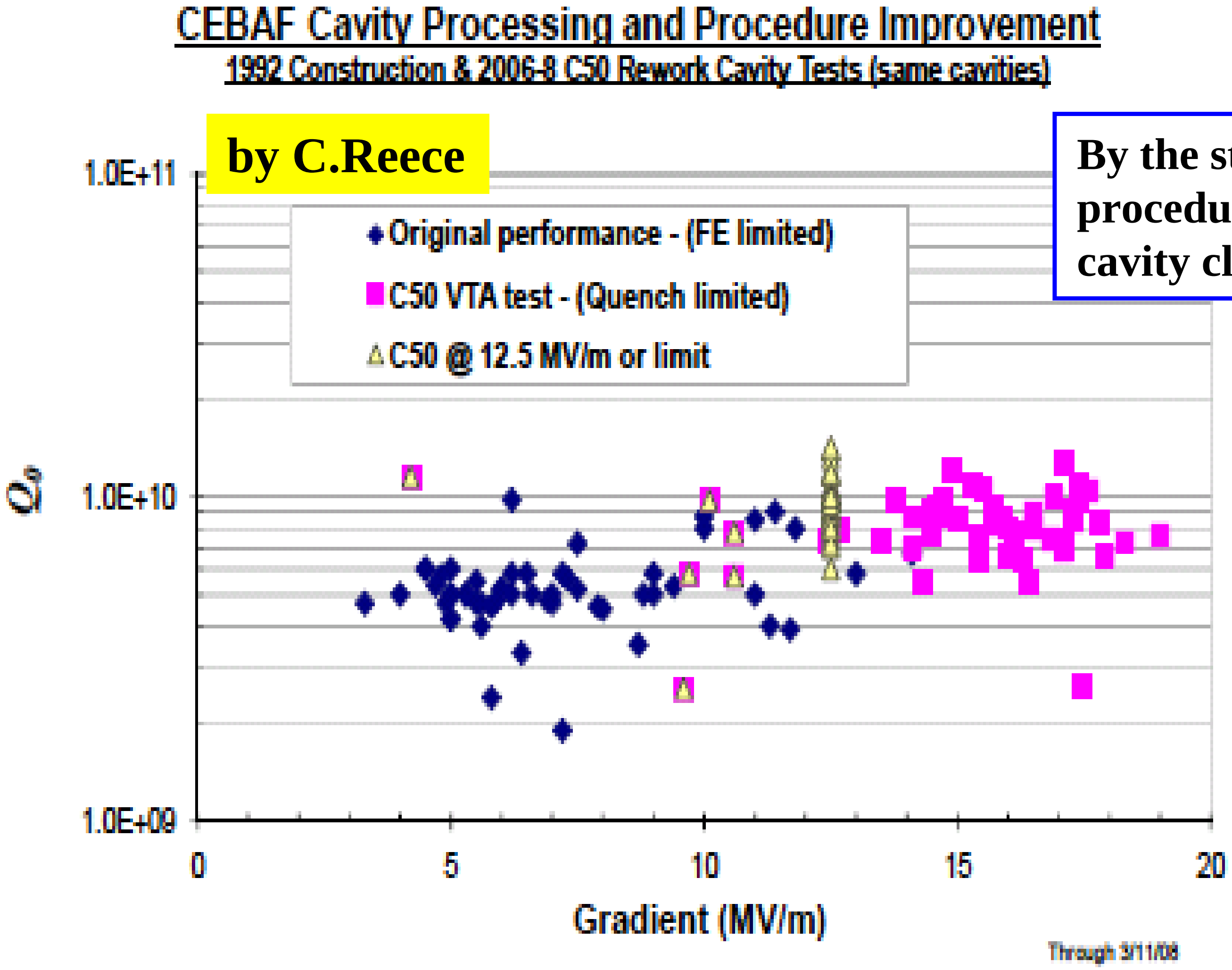


Figure 5. Cavity Q and gradient just below quench.

CEBAF Cavity Rework (12GeV CEBAF Upgrade) by the State of Art Technology

http://www.jlab.org/highlights/acc.html





By the state-of-the-art procedures:BCP+ "HPR" +Improved cavity clean assembly

12GeV CEBAF Upgrade

Old cryomodule+ Reworked ones(12.5MV/m) ⇒ 6GeV/5 turns

Add new HG cryomodule 18MV/mx80 ⇒ 1GeV/turn

12GeV/5.5turn

To secure the 6 GeV base of CEBAF, the C50 program has been done. The 10 weakest original cryomodules have been reworked and returned to operation in CEBAF.
This now makes possible a robust 6 GeV physics program.
This is 1.2 GeV/turn x 5 turns = 6 GeV.

12GeV CEBAF Upgrade LL-shape Cavity

1.5GHz, LL-shape, 7-Cell, 80 cavities(10Module), by J.Preble et al., SRF2009

1GeV/one turn, Eacc=19.2 MV/m (included a margin),

By the state of the art technology:

LL-shape+ EP+Bake +
HPR+Improved clean assembly

RF parameters	CEBAF	CEBAF Upgrade
f_o[MHz]	1497.0	1497.0
k_{CC}[%]	3.29	1.49
Ep/Eacc	2.56	2.17
Hp/Eacc [mT/(MV/m)]	4.56	3.74
R/G [Ω]	96.5	128.8
Target	5MV/m, Qo > 2.4E+9,	19.2MV/m Qo > 8.0E+9

Test in Horizontal Cryomodule(BCP'ed cavity)

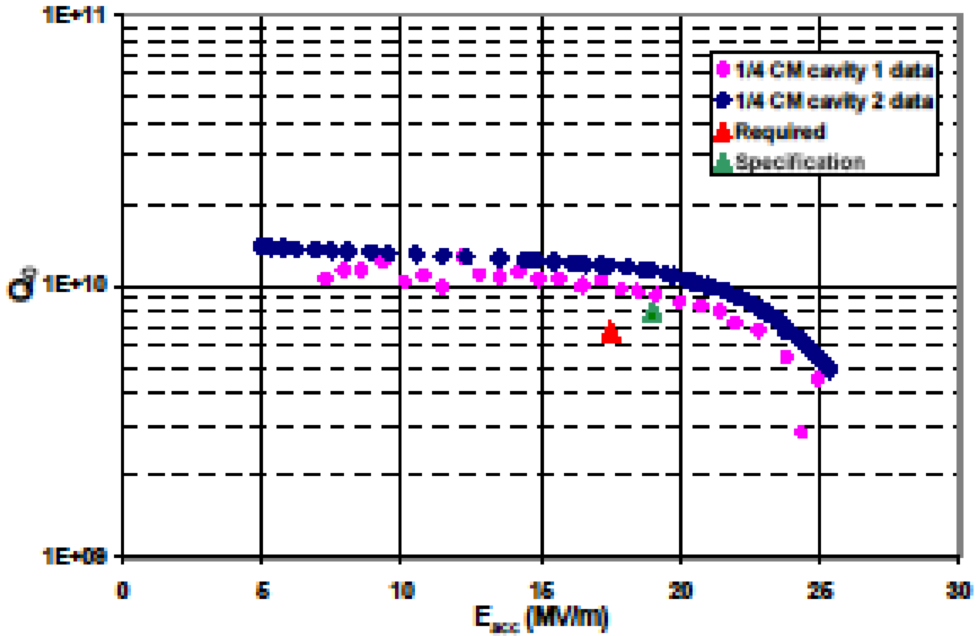


Figure 2: Cavity Performance in the HTB Test.

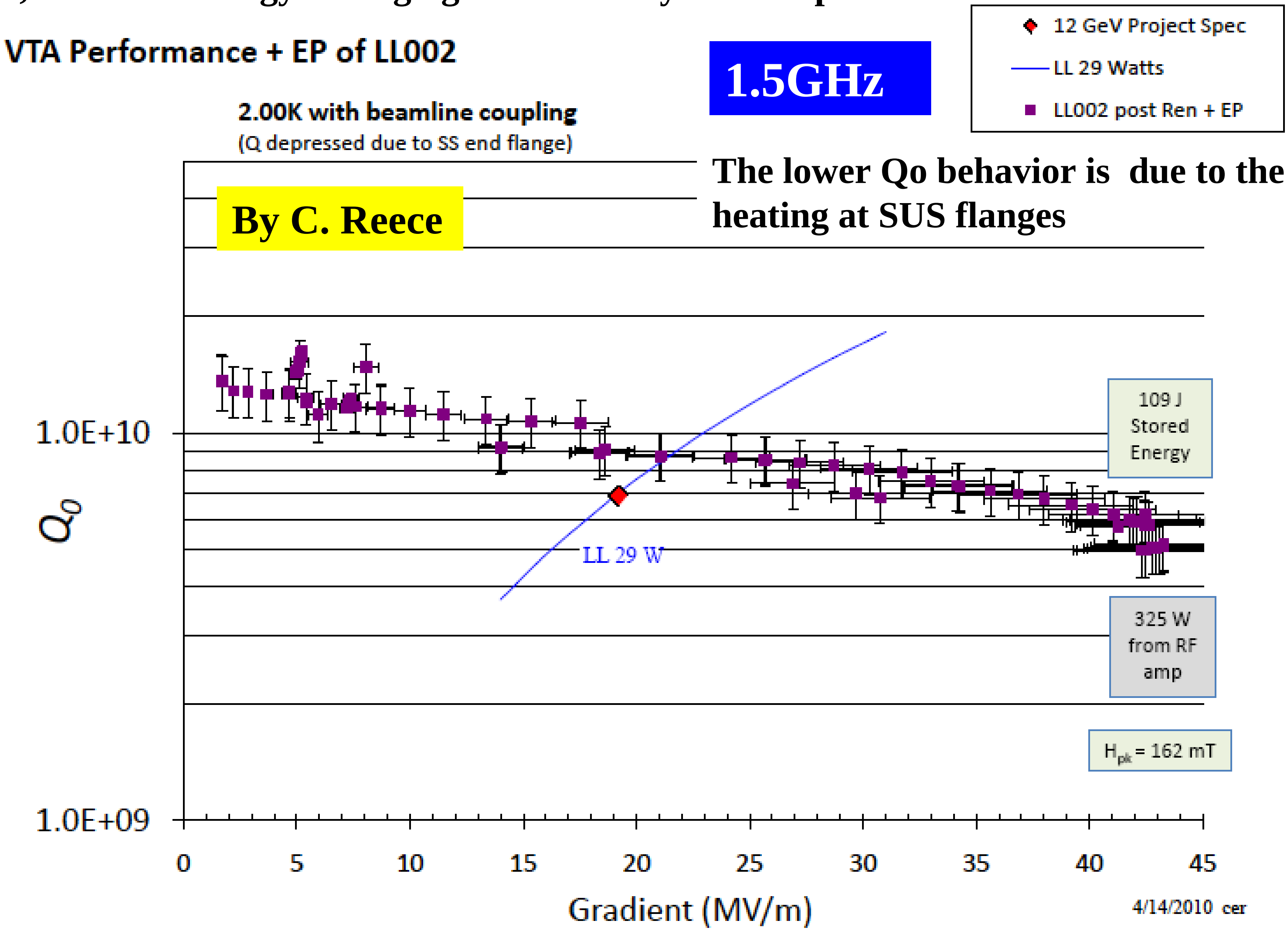
Demonstration of the high gradient performance with LL-shape + EP+ Bake in the CEBAF Upgrade Cavity(HG 7-cell)

So far, the best strategy for high gradient cavity: LL-shape + EP + Bake

1.5GHz

By C. Reece

The lower Qo behavior is due to the heating at SUS flanges



Performance advance seen in the 12GeV CEBAF Upgrade by the state of art Technology

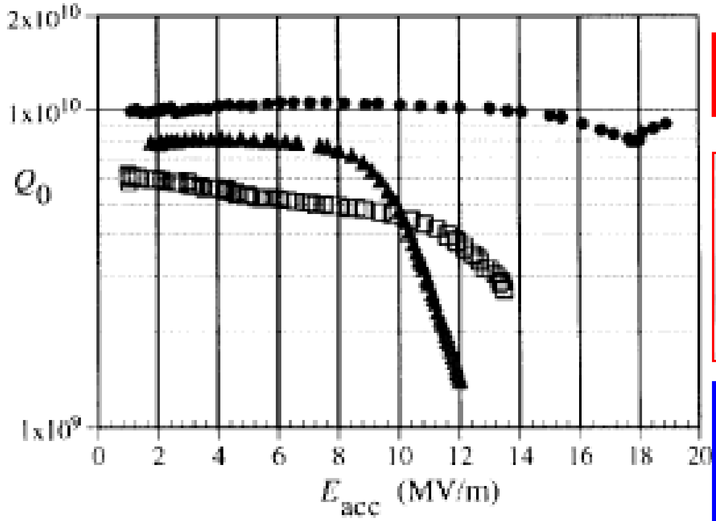
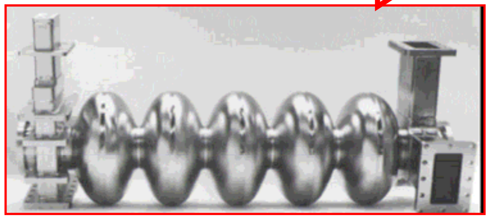
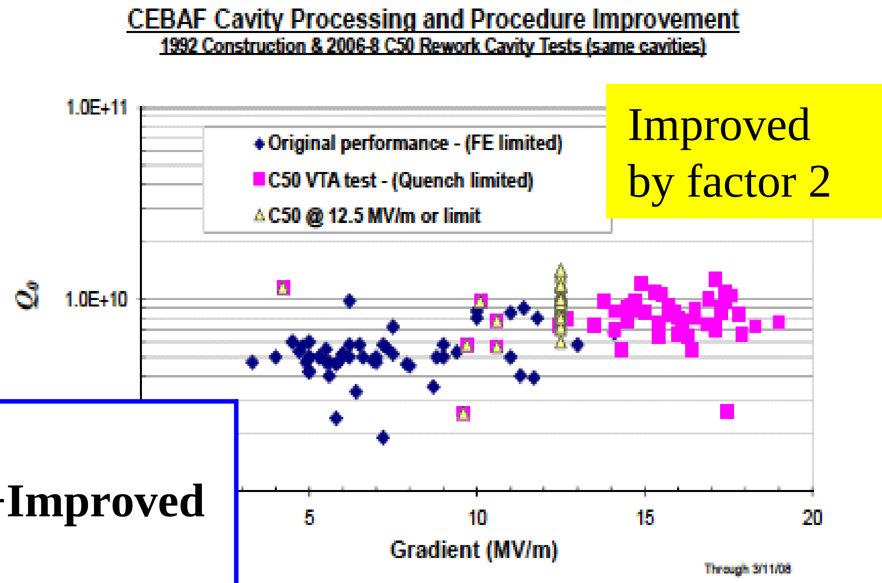


Figure 1. Typical cavity performance in vertical testing.

Mainly HPR

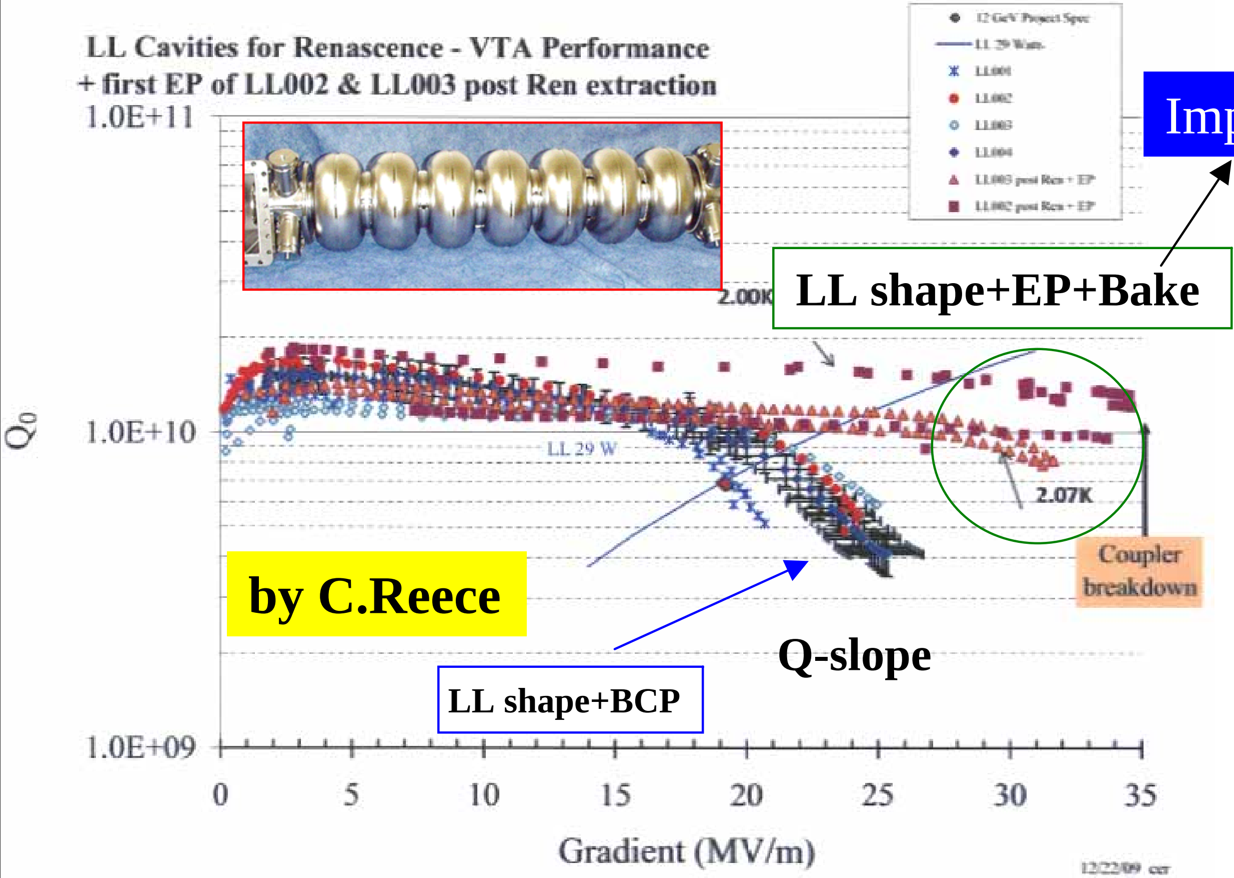




Improved by factor 2

By the state-of-the-art procedures:BCP+HPR+Improved cavity clean assembly

Improved by factor 4



1)Higher gradient due to LL shape.

2) High Q performance due to LL shape

3) Possible 25MV/m operation by EP+Baking, which brings a big operation margin.

4) State-of-art technology pushes the performance very much.

ILC activity @ JLAB

by R.L.Geng et al., SRF2007 and 2009

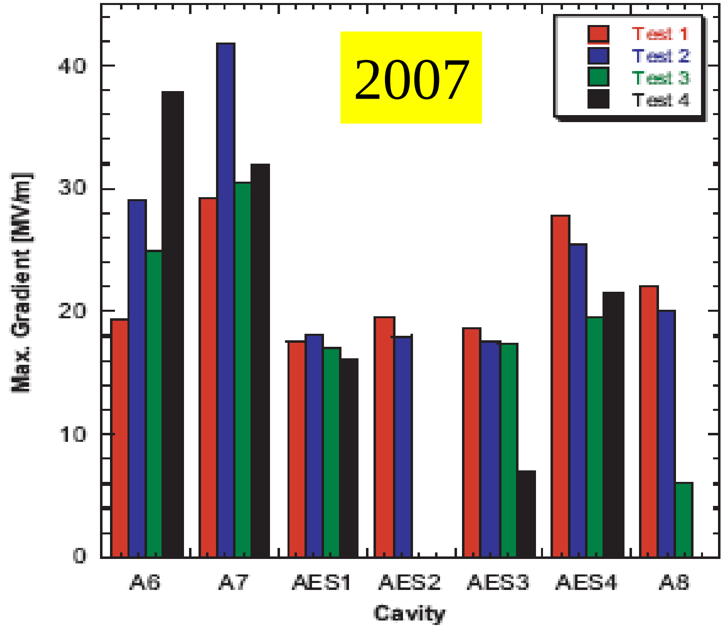
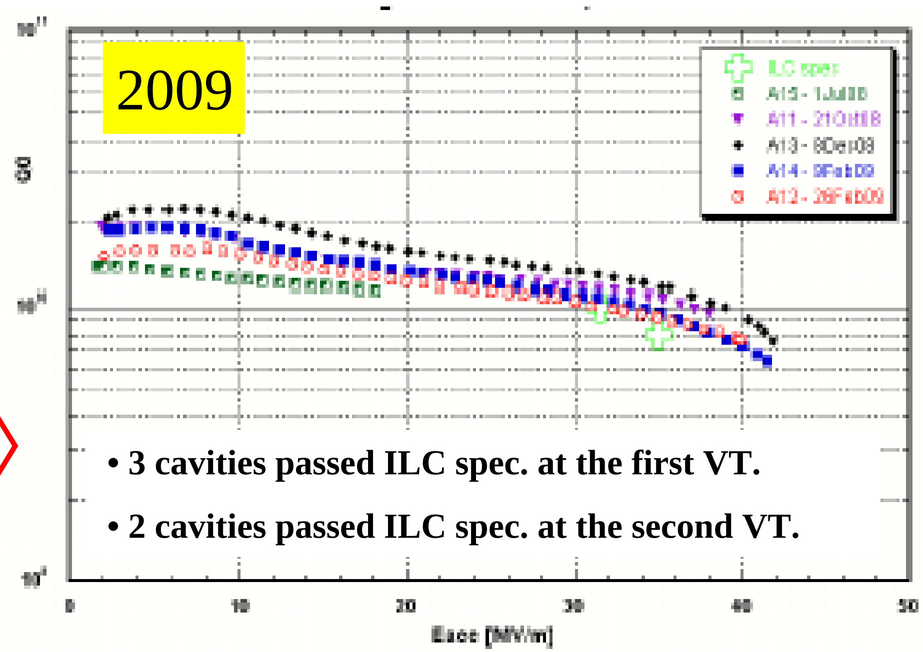


Figure 2: Maximum gradients achieved by 9-cell cavities.

Much improved



- **3 cavities passed ILC spec. at the first VT.**
- **2 cavities passed ILC spec. at the second VT.**

Figure 3: Performance of 5 new cavities manufactured by ACCEL and EP processed and tested since July 2008 at JLab. Error bars are not shown for clarity.

Nb_xO_y granules produced during EP were source of FE.

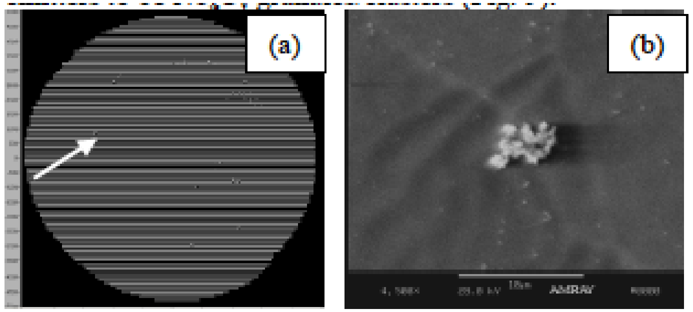


Figure 9: (a) Field emitters revealed by scanning a high-voltage tip over a niobium surface electro polished together with a 9-cell cavity. (b) SEM image of the field emitter (indicated by arrow in Fig. 3a); EDX analysis indicates no foreign elements except niobium and oxide.

The integration of the improved cavity fabrication, improved EP and post-EP cleaning and other clean cavity assembly is pushing the gradient yield up to >35MV/m by the first or send processing passes.

More up-date results will be given on ILC activities by C.Ginsburg.

SNS Cavity Performanc by J.Preble et al., SRF2009

RF parameters	β=0.61	β=0.81
f_o[MHz]	805	805
k_{CC}[%]	1.52	1.52
Ep/Eacc	2.66	2.14
Hp/Eacc [mT/(MV/m)]	5.44	4.58
R/G [Ω]	49.2	83.8
Target Gradient [MV/m]	10.1	15.8
Target Qo	> $5.0x10^9$	> $5.0x10^9$

Figure 7: SNS β=0.61 three-cavity string assembled in the clean room

Medium-β cavity, 11 medium-β (0.61) Cryomodules of 3 cavities each, totally 33 cavities.

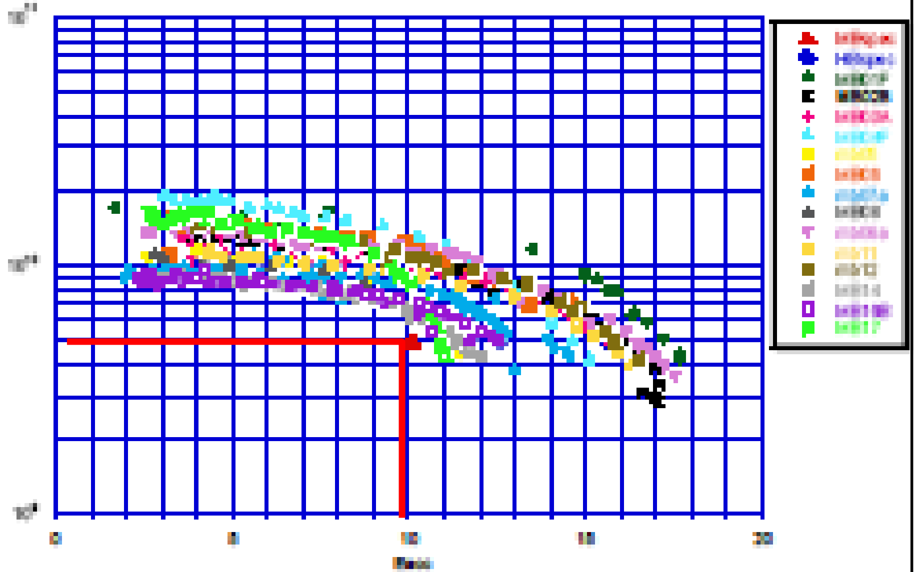


Figure 4. Q_0 vs E_{acc} for SNS Medium Beta Cavities

High-β cavity, 12 high-β (0.81) Cryomodules of 4 cavities each, totally 48 cavities.

by J.R.Delayen et al., LINAC04

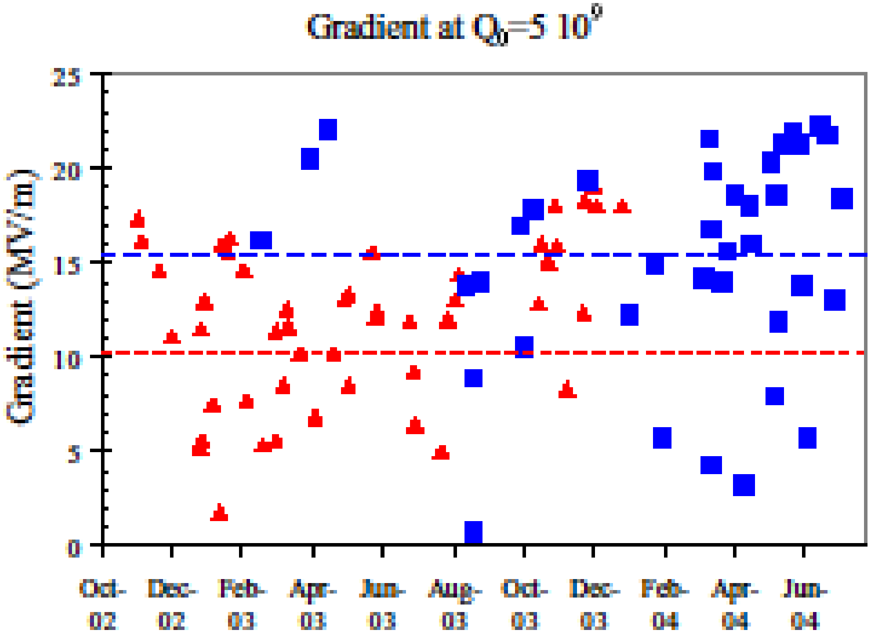


Figure 2: Gradient of SNS medium (triangles) and high (squares) β cavities measured at the Q_o specification of 5 x 10^9 during all vertical cavity tests at 2.1 K. The lower (upper) curve represents the gradient specifications for the medium (high) β cavities, respectively.

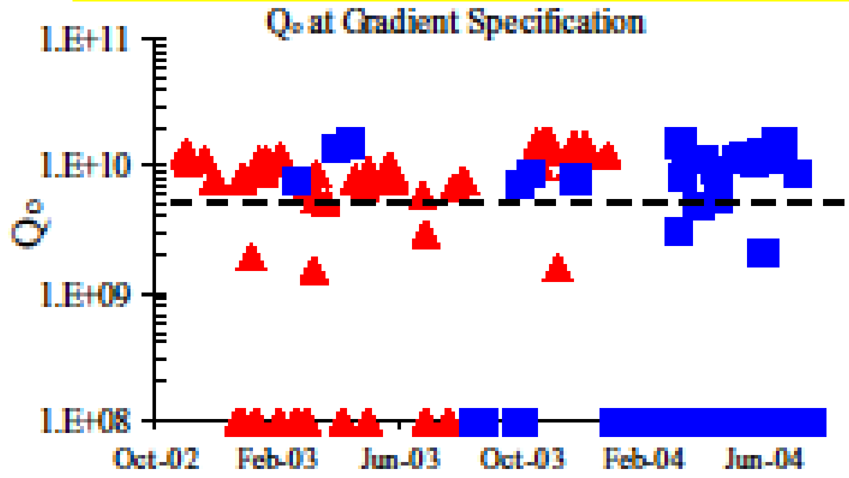


Figure 3: Cavity Q_o measured at the respective gradient specification for SNS medium- (triangles) and high- (squares) β cavities. Cavities that did not meet the required gradient specification are shown with a Q_o of 1 x 10^8.

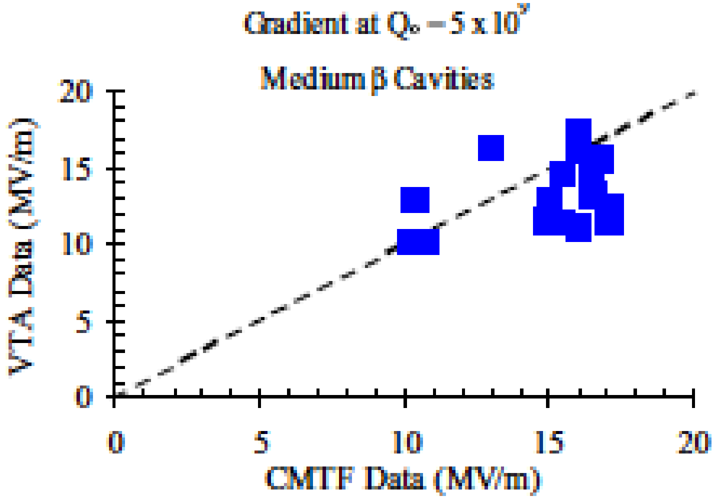


Figure 6: Comparison of measured cavity gradient at the Q_o specification of 5 x 10^9 for the SNS medium-β cavities, as measured in CW mode during vertical dewar tests and in pulsed mode in the completed cryomodule.

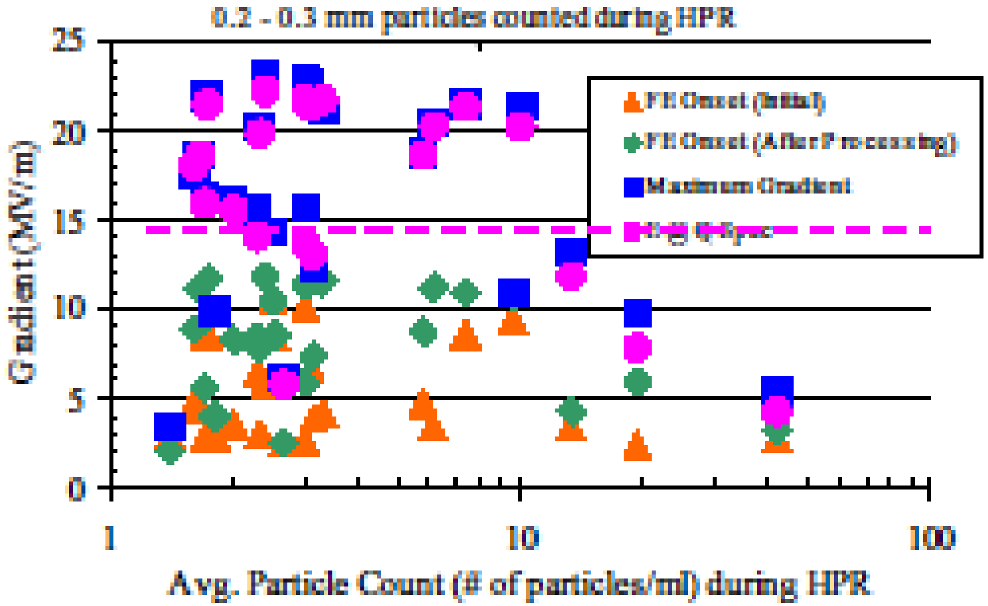


Figure 7: Effect of particulate density in the water during high-pressure rinsing on various cavity fields for the SNS high-β cavities.

Cavity performance in operation at SNS

by Sang-ho Kim, LINAC08

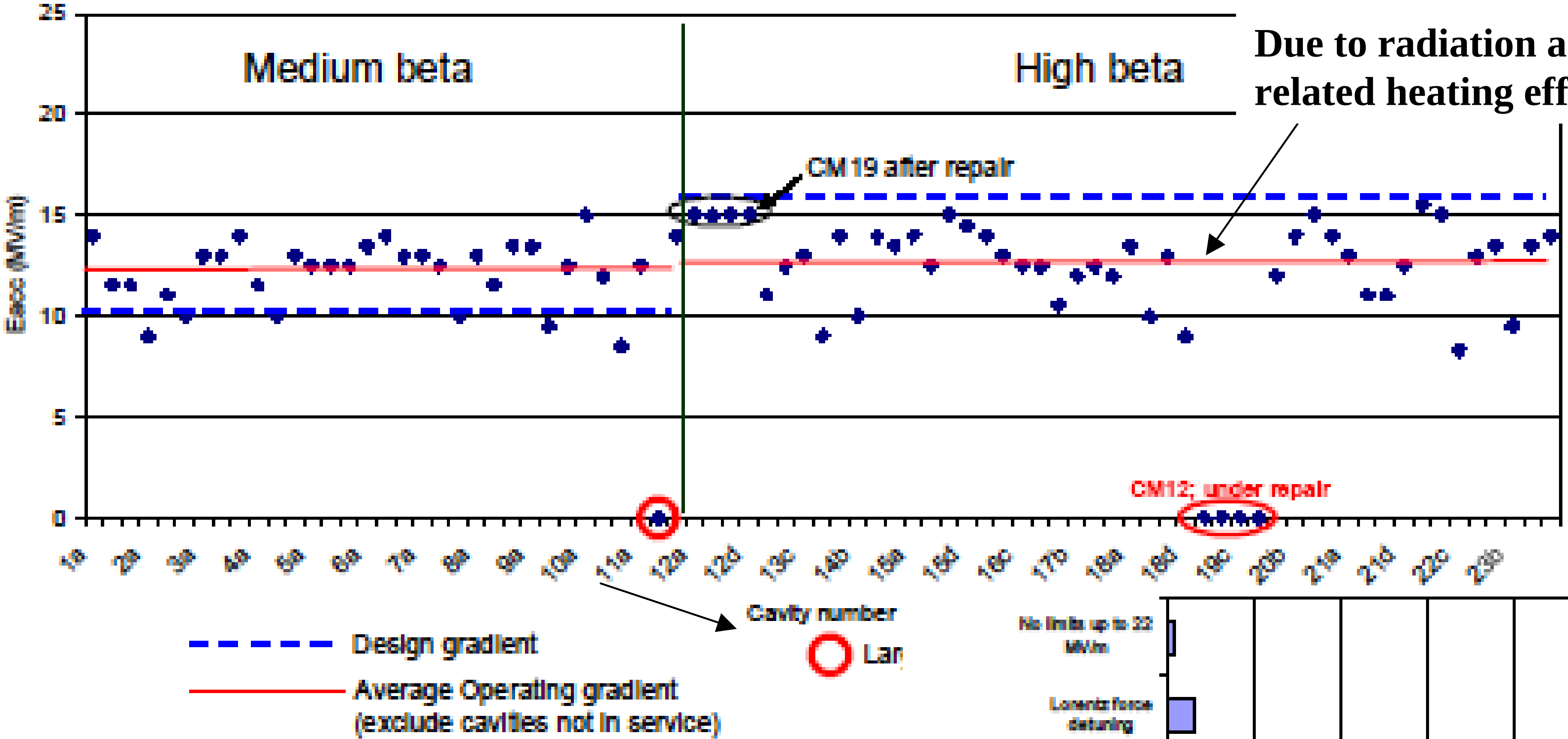


Figure 2: Operating setpoints of SCL SRF cavities at 60

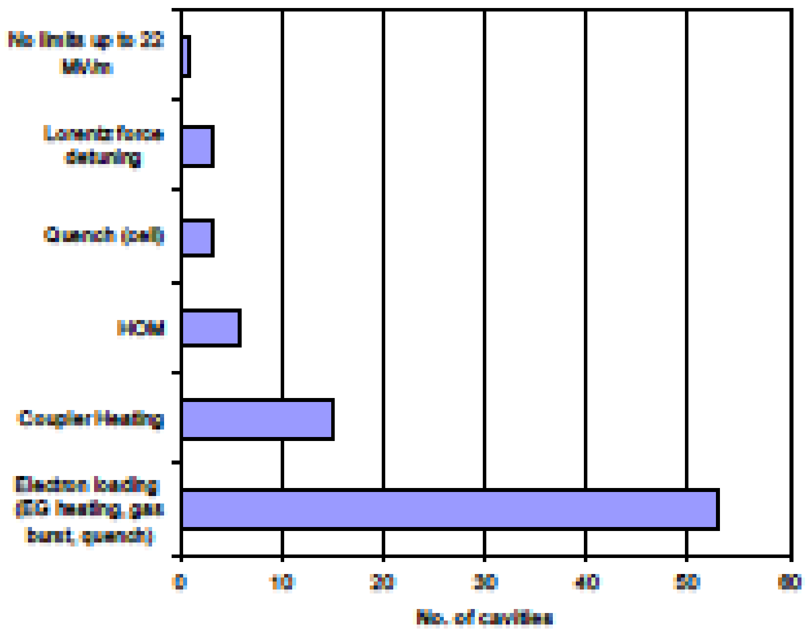


Figure 6: Statistics of limiting factors at 60 Hz collective condition.

Cornell ERL Injector 2-Cell Cavities

by H.Padamsee et al., EPAC04

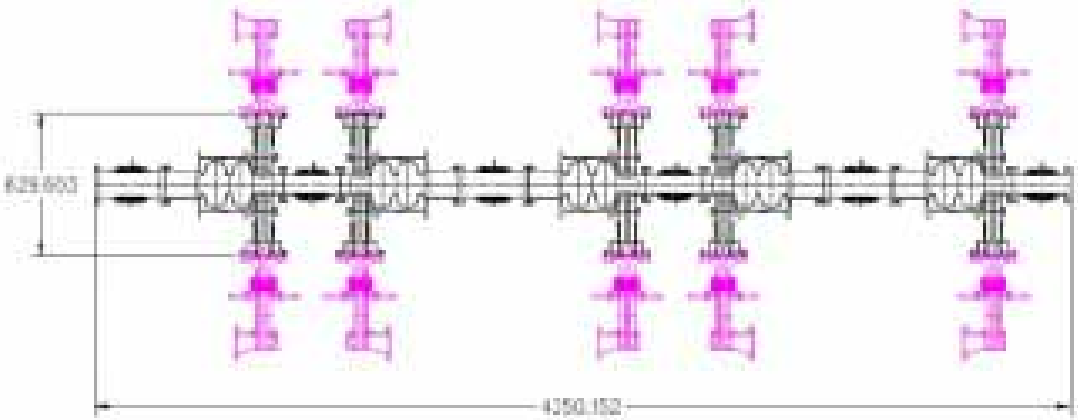


Figure 1: Layout of the 5-cavity string of the Cornell ERL prototype injector.

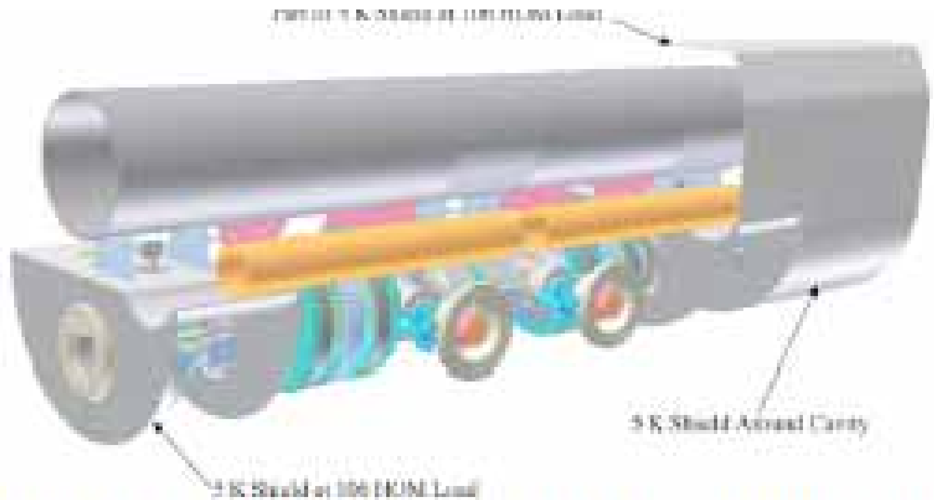


Fig. 8: Location of heat shields in the injector cryomodule.

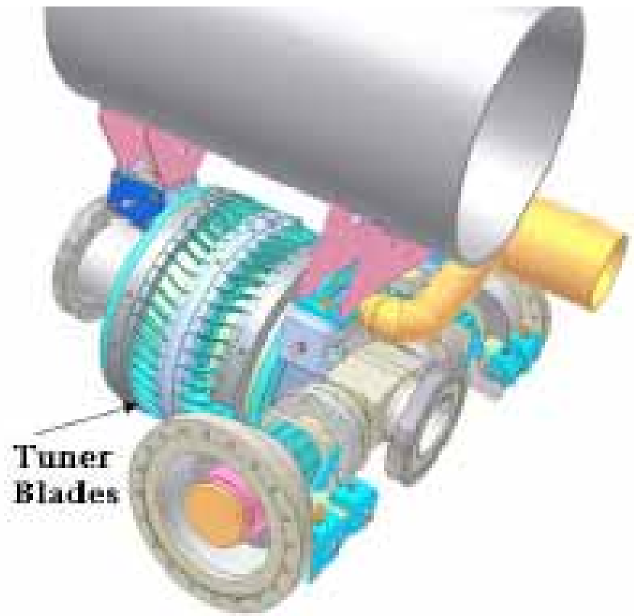


Fig. 7: One cavity assembly showing helium vessel, blade tuner, input couplers and connections to the helium input and output lines.

(a) Chemical etching (b) High-pressure rinsing

Figure 5: 2-cell cavity processing: (a) Chemical etching with BCP1:1:2; (b) High-pressure water rinsing.

by R.L.Geng et al., PAC07

Large BP is suffered by MP!

Figure 2: 2-cell cavity before and after welding the helium vessel.

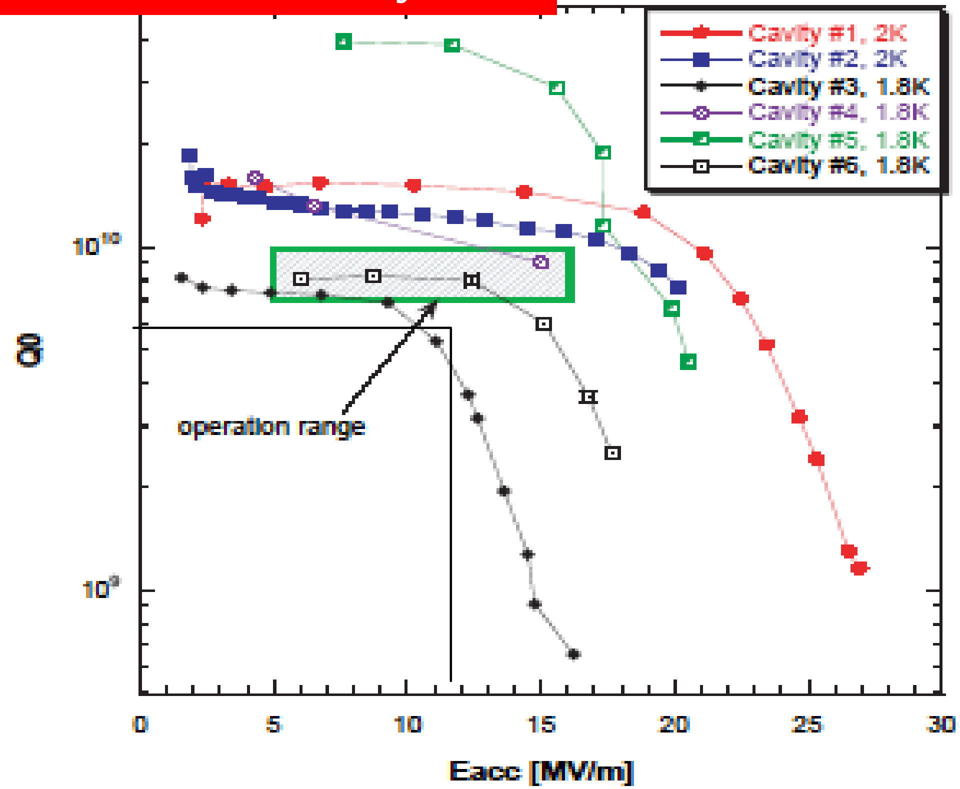


Table 1: RF properties of 2-cell superconducting cavities

Frequency	1300 MHz
Number of cells	2
R/Q	218 Ohm
E_{pk}/E_{acc}	1.94
H_{pk}/E_{acc}	42.8 Oe/(MV/m)
Coupling cell to cell	0.7 %
Q_0 *at 2 K*	$> 5\times10^9$
Twin-Input coupler Q_{ext}	4.6×10^4 / 4.1×10^5
Accelerating voltage	1 MV / 3 MV
Max. power transferred to beam	100 kW

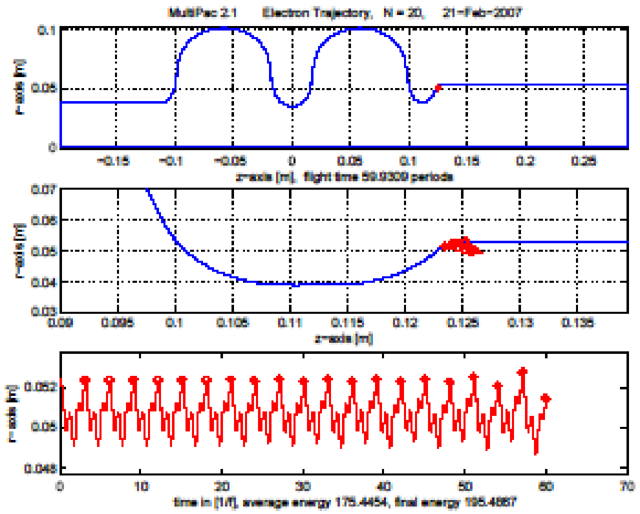


Figure 7: Multipactor in the 2-cell cavity. E_{acc}=6.5 MV/m. Upper: cavity model with beam tubes and location of the multipactor; Middle: magnified multipactor location and electron trajectories; Lower: time interval between impacts and the impacting energy.

FLASH/EUR XFEL Cavity Performance

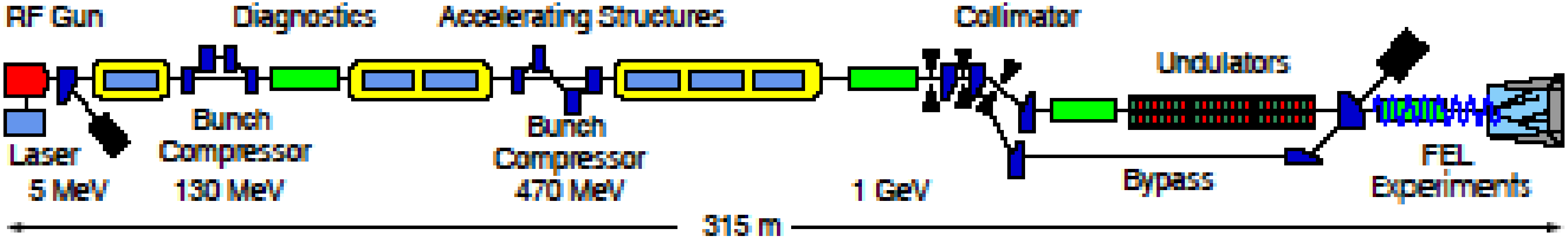
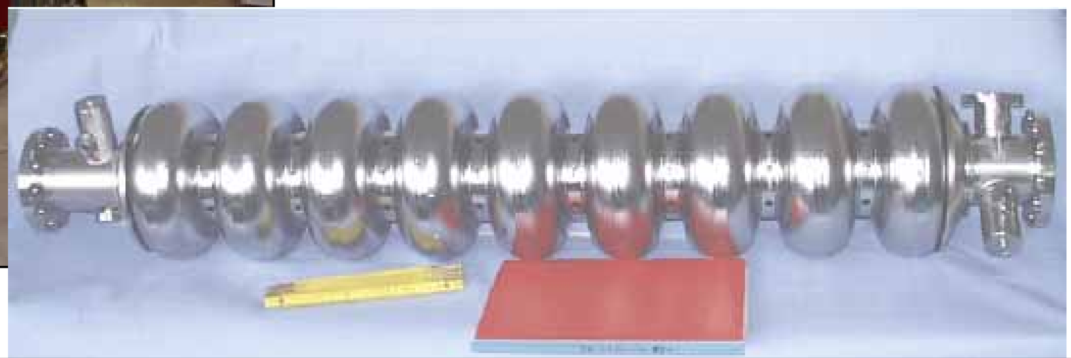


Figure 1: Layout of the FLASH linac including the experimental hall (not to scale).

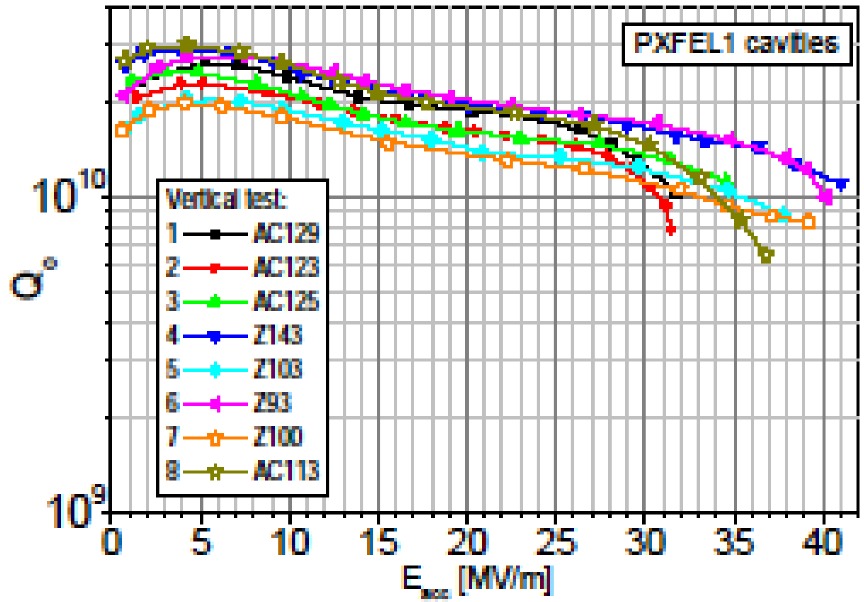


Satisfied XFEL Specification in the Cryomodule Test

Good news

Cavity integration satisfies the XFEL spec!

by D.Kostin et al., SRF2009



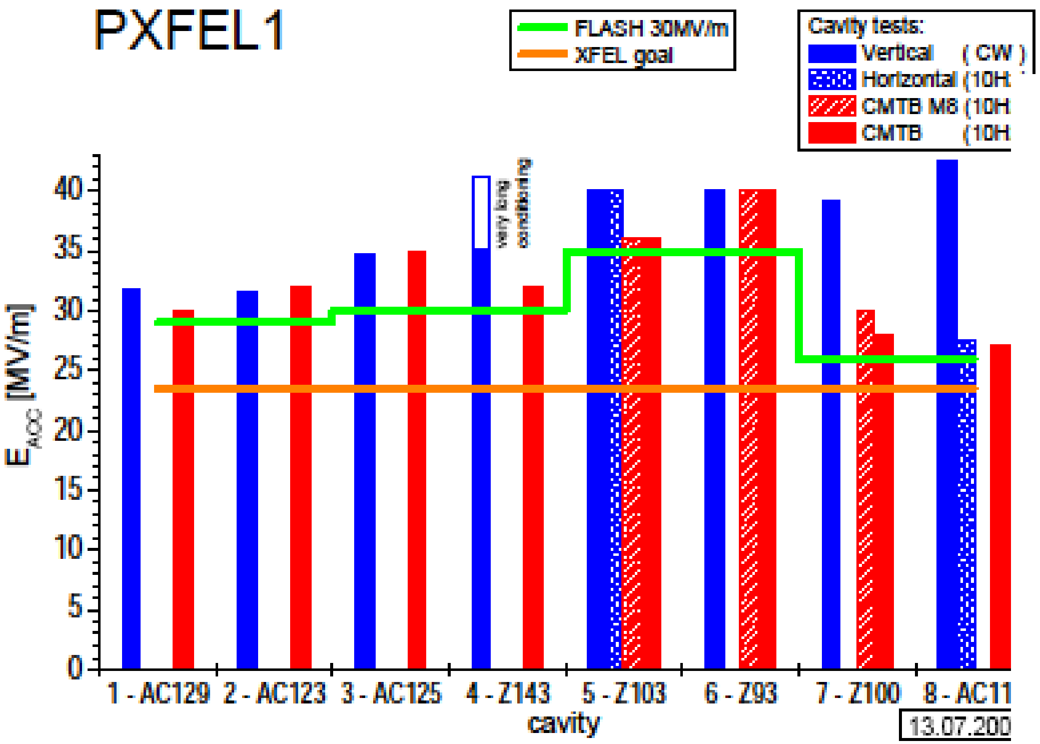


Figure 4: Test results of accelerator module PXFEL1.

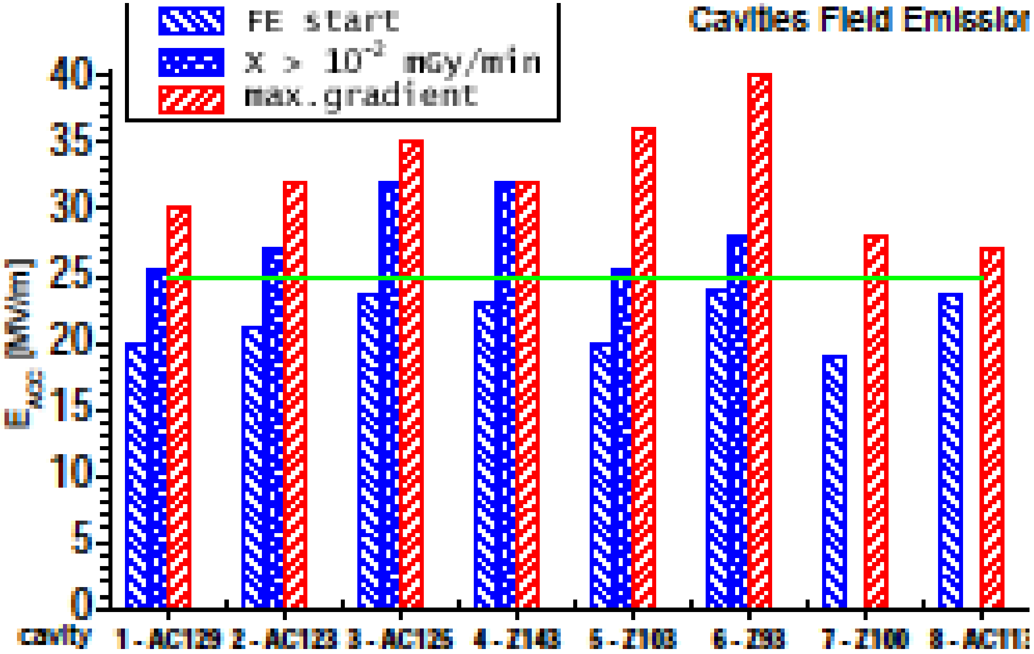


Figure 11: Single cavities test: cavities field emission.

ANALYSIS OF RF RESULTS OF RECENT NINE-CELL CAVITIES AT DESY

D. Reschke#, L. Lilje, H. Weise, DESY, 22603 Hamburg, Germany

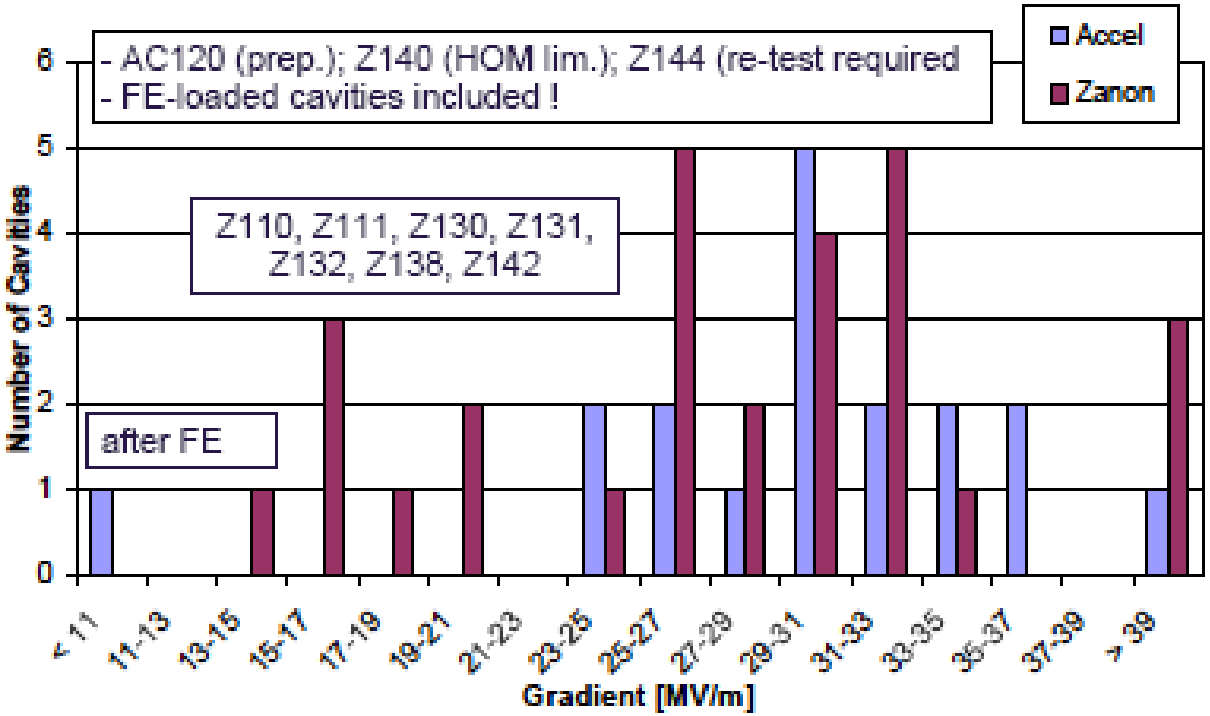


Figure 3: Histogram of maximum gradients of last vertical RF acceptance test depending on cavity vendor.

Zanon cavities are still suffered by defects on the heat affect zone of equator EBW.

EBW defects on Heat Affected Zone limiting Eacc < 20MV/m

by S.Aderhold, SRF2009

Matched case1:Limited at 16.6MV/m, 700μm dia, 200μm deep, Z130 Cell#5 Equator

Figure 1: Quench location found by T-map (left) and optical inspection picture of respective area (right) in Z130.

Similar efforts are going on KEK-STF, Jlab, FNAL and Cornell in the ILC activities.

Sub mm sized defect usually found around the EBW heat affected zone.

Pass-band modes meas. @VT

Find out candidate cells limiting the cavity performance

Thermometry system

Find out heating locations in the cells

Optical inspection(eg. Kyoto camera)

Take optical images at the defects

Matched case2:Limited at 20.6MV/m, 300x500μm dia, 200μm deep, Z142 Cell#6 Equator

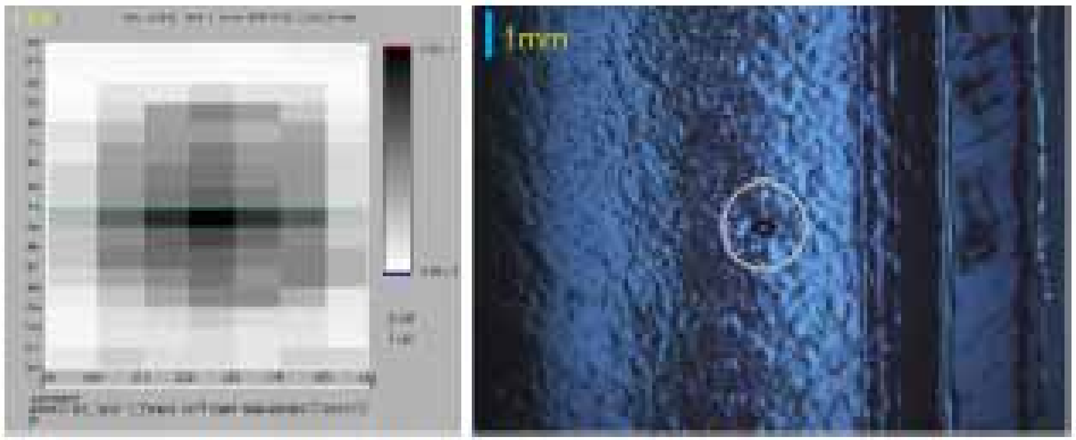
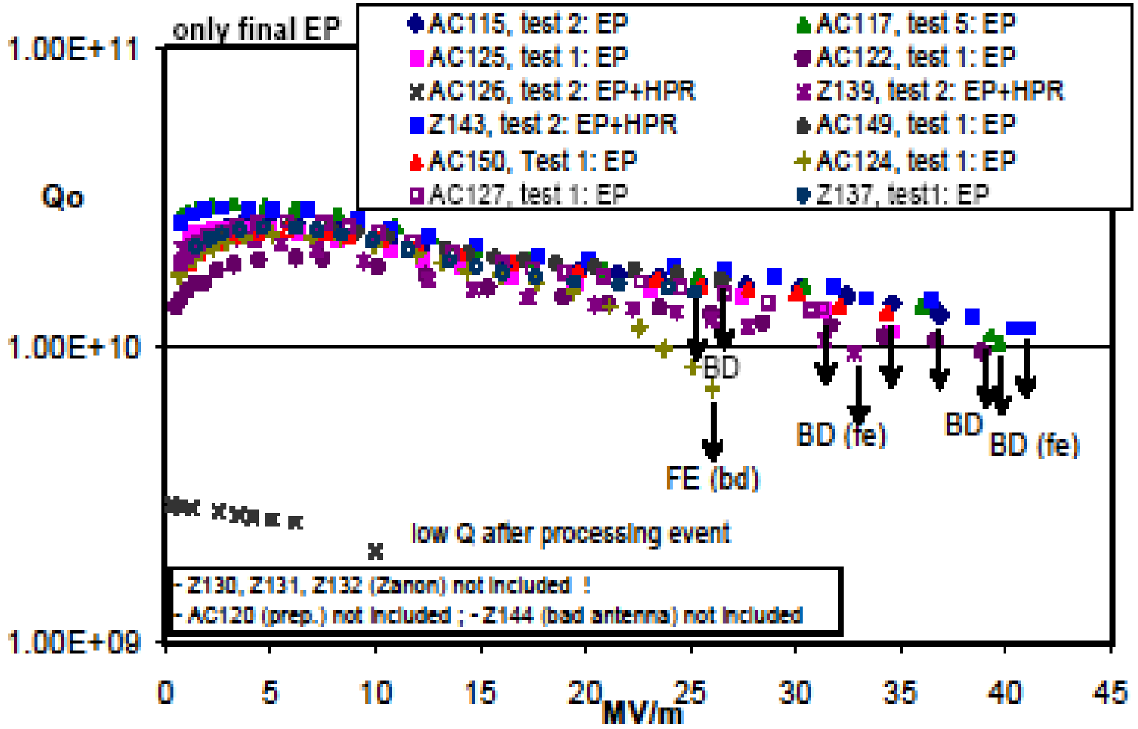


Figure 2: Quench location found by T-map (left) and optical inspection picture of respective area (right) in Z142.

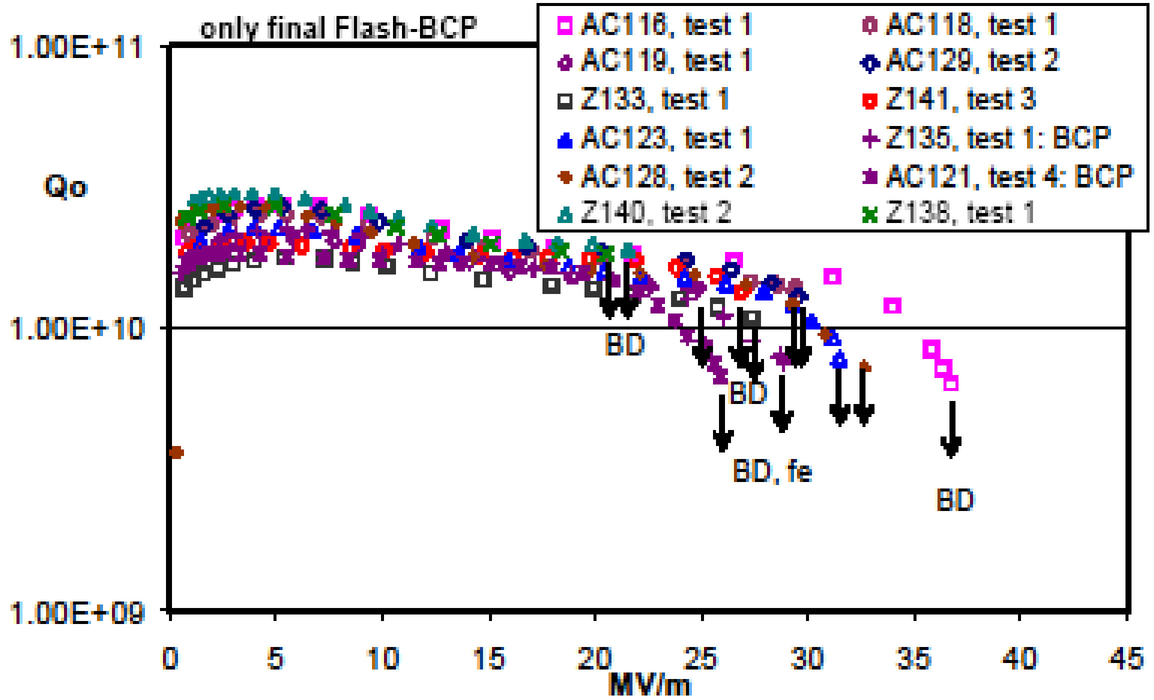
Scatter at Eacc > 25MV/m

by D.Reschke et al. SRF2009



The hard quench > Eacc 25MV/m is much more concerned issue for ILC specification

Flash BCP(10μm) still happens Q-slope.



An example of promising technology not yet applied to any project

Search of the surface by Kyoto camera to undender stand the limitation of Eavcc > 25MV/m.

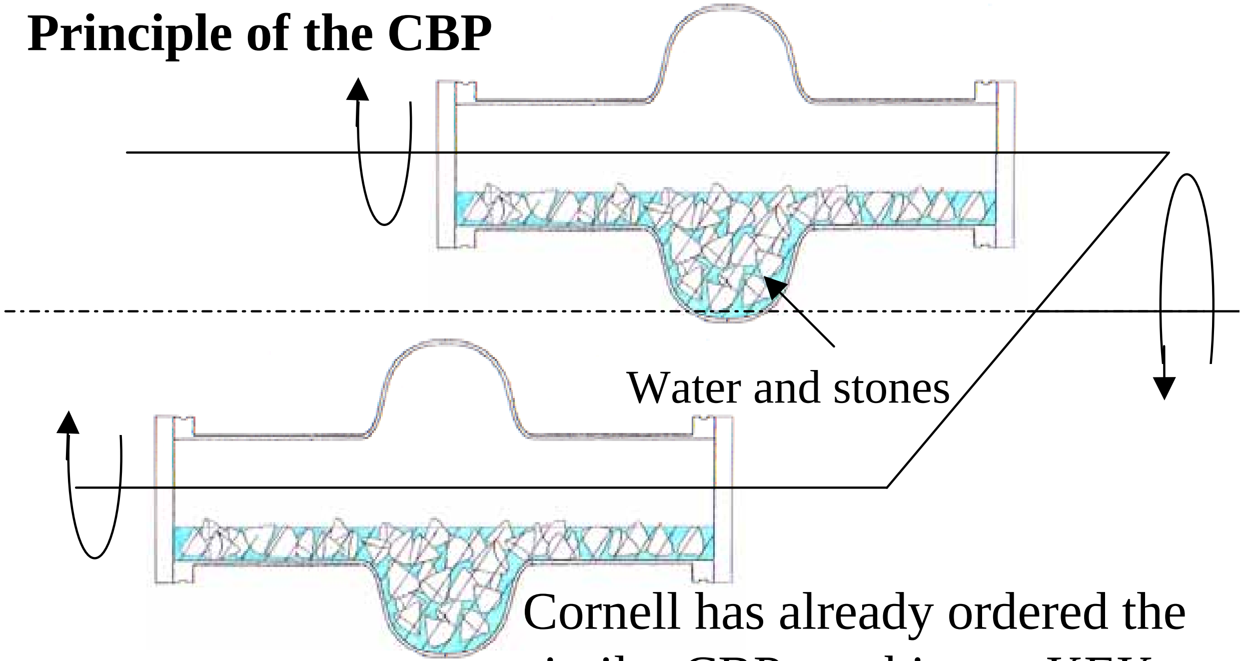
Limited 25.2MV/m, Z137 Cell#1 at heat affect zone next to the equator, but not seen clear defects by optical inspection. Micron sized defect ? Resolution is not enough?

Figure 3: Equator welding seam of cell 1 in Z137: Before chemical treatment (left), after main EP (center) and after final EP (right).

KEK practical approach : Grinding all inner surfaces before EP.

Powerful mechanical grinding: CBP or Tumbling

Principle of the CBP



Cornell has already ordered the similar CBP machine as KEK.

Not yet applied to any project but a very much promising technology.

Jlab, FNAL and Cornell have started to study on the technology.

You will have more information from P.Kneisel (Jlab) and G.Hoffstaetter (Cornell) in this meeting.

CBP machine @ KEK, WG-5

Tumbling machine @ Jlab

Summary

- We have seen a very nice technology feed-back to projects in Jlab contributions.
- The cavity performance is pushed up very much by the state-of-art technology.
- Several new technologies not yet applied might push up the cavity performance close to the theoretical limit in near future.

Performance Analysis of SNS Cavities at Acceptance VT

by J.R.Delayen et al., LINAC04

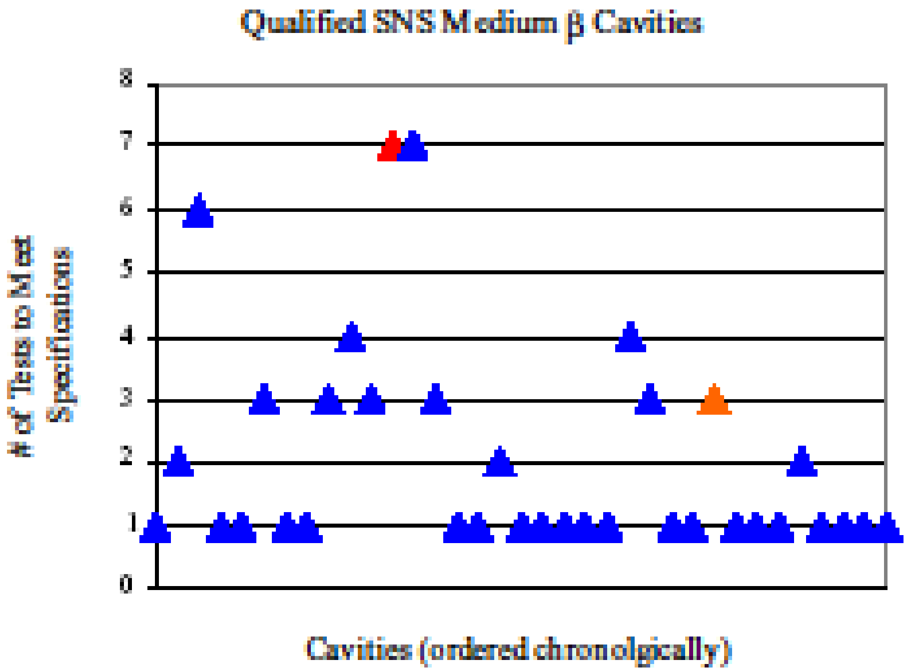


Figure 4: Number of vertical dewar tests required to reach acceptable cavity performance levels for each SNS medium-β cavity, ordered chronologically by date of 1st test.

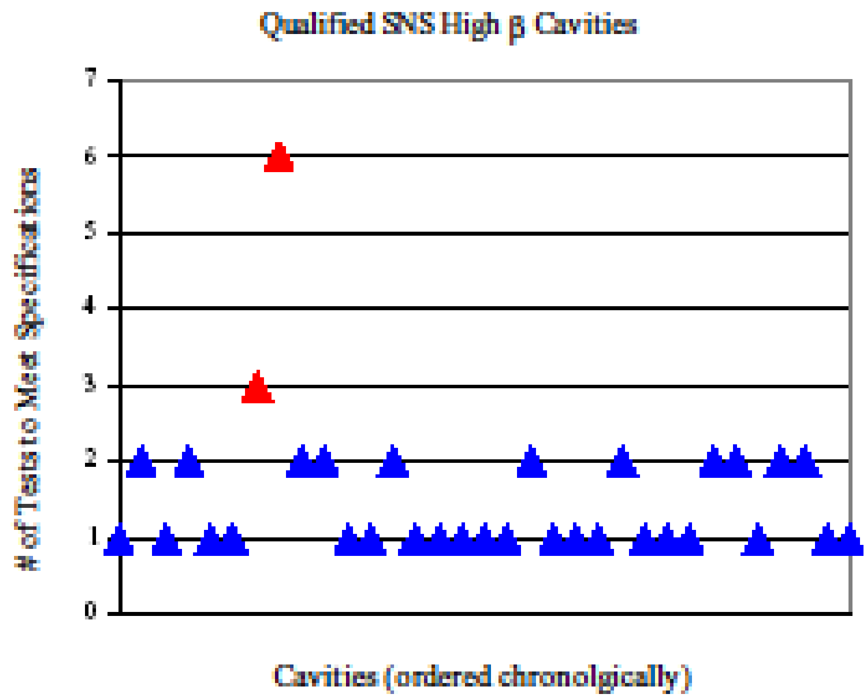


Figure 5: Number of vertical dewar tests required to reach acceptable cavity performance levels for each SNS high-β cavity, ordered chronologically by date of 1st test. The cavities denoted in red were used for additional procedure tests.

MP: NO multipacting occurred on the medium beta cavities, but 31/34 cavities on the high beta cavity showed MP at 9.5-18.6MV/m.

Promising cure technology against High Field Q-slope

EP or BCP+800^{O}C annealing+Baking might cure the high field Q-slope.

by G.Ciovati, SRF2009

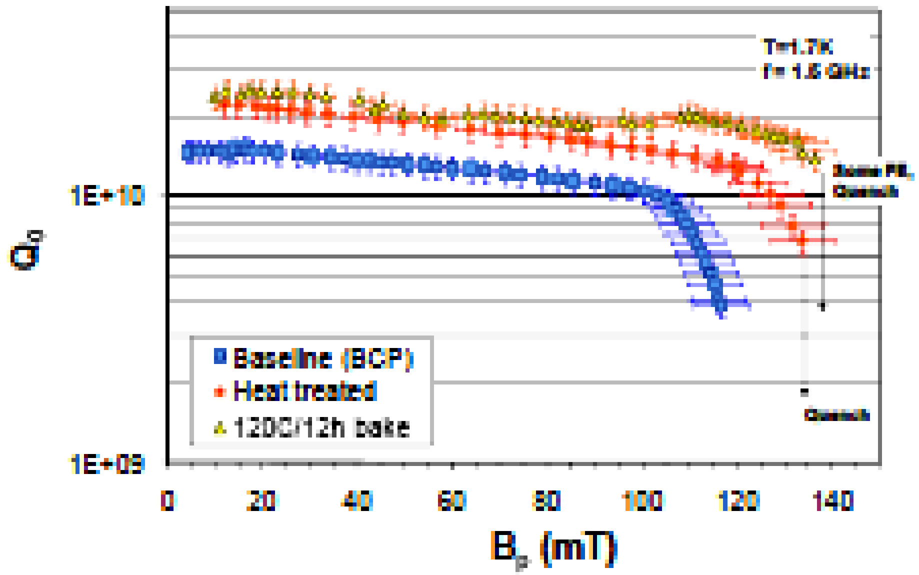


Figure 6: $Q_0(B_p)$ curve measured at 1.7 K on a CEBAF single-cell cavity made of large-grain Nb before and after the heat-treatment shown in Fig. 5 and additional low-temperature baking.

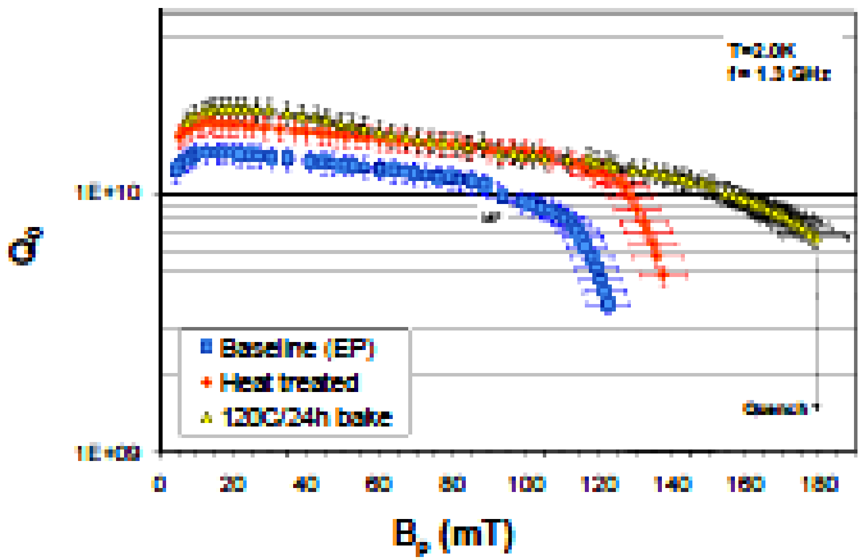


Figure 7: $Q_0(B_p)$ curve measured at 2.0 K on an ILC single-cell cavity (AES001) made of fine-grain Nb before and after the heat-treatment shown in Fig. 5 (but without N_2 injection at 400 °C) and additional low-temperature baking.

Experiment confirmed that Oxygen dose not diffuse as estimated by diffusion mode. Oxygen diffusion model can't explain the Q-slope.

Q-slope might be explain by vortex moving or hydrogen trapping around dislocations. High temperature annealing using clean furnace + Baking is promising to eliminate the high field Q-slope.