Test Results of β<1 Superconducting Elliptical Cavities : Experience and Lessons Learned

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Background/Scope

- SC option for SNS considered & discussed during workshop in August 1999
- SC cavity prototyping plan presented Nov. 1999
- SC option chosen in spring of 2000, cell shape in Apr. '00
- Work begins on prototype cavities
  - Cu medium & high β models
  - Nb medium β prototypes (4)
  - Nb high β prototypes (2)
- Tests on medium β prototypes begin – Oct '00
- Tests on high β prototype begin – Apr. '01
- Tests of medium β production cavities (33) begin – Sep. '02
- Tests on high β production cavities (48) begin – Mar. '03

5 Years from cell shape to completion of CM production

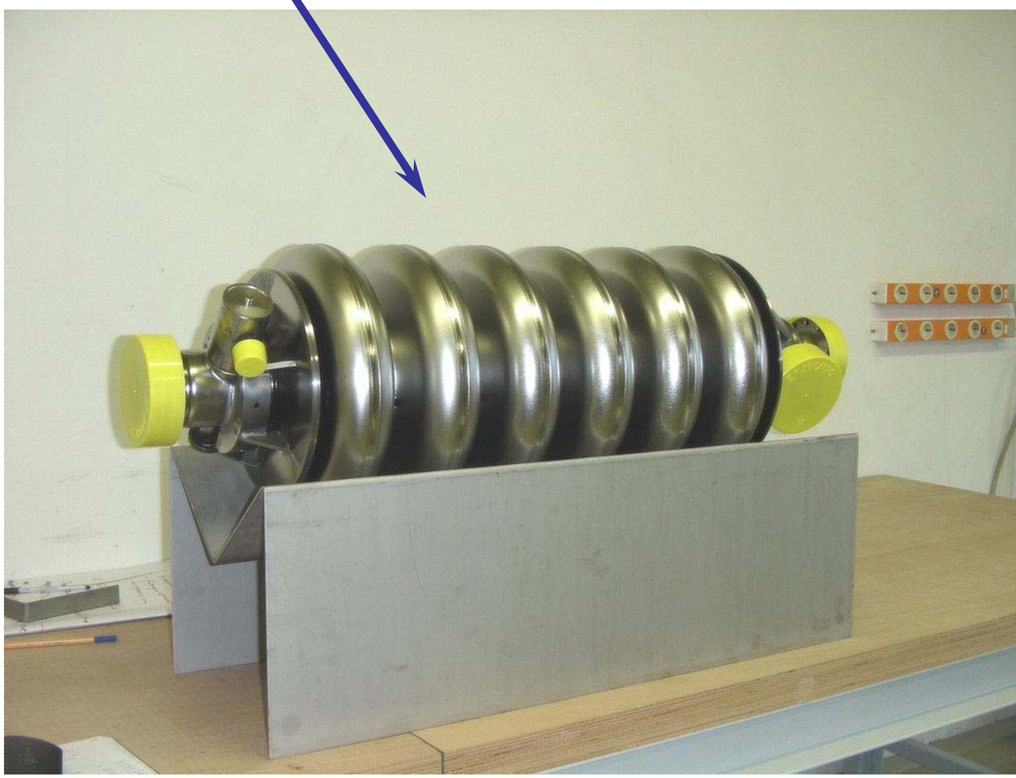
Cavity Performance Parameters

Parameter	Cavity Type β= 0.61	β=0.81
Operating Gradient (MV/m)	10.2	15.6
Q_o spec at Operating Gradient	$\geq 5 \times 10^9$	$\geq 5 \times 10^9$
E_{peak} (MV/m)	27.6	34.2
H_{peak} (mT)	58.0	73.2
E_{peak}/E_{acc}	2.71	2.19
B_{peak}/E_{acc} (mT/(MV/m))	5.72	4.72
Operating Temperature (K)	2.1	2.1

SNS Production Cavities

"Bare" Medium β

Medium & High β In He Vessels



Vertical Cavity Test Facility - VTA

- 6 shielded dewars, with movable radiation shields, instrumented w/ LHe level and pressure sensors, thermometry, and radiation detectors (γ and n's)
- 500W 805MHz RF system can be routed to 2 of these 6 dewars for production testing of SNS cavities, fully interlocked
- Closed cycle LHe supply, > 8 g/s fill rate at 4K (165W eq.)
- Pumpdown to 2K using 7-8 g/sec Kinney pump
  - **from 300K to 2K and ready to test in ~ 6 hours!**
- PC w/ LV for RF test DAQ
- Total test turnaround time ~ 24 hours.
- Capability of 5 SNS tests/week (w/ no other LHe demands)

Medium β Cavity Results

Production testing began in fall of 2002 with an initial focus on process/test development, cavity frequencies (pre, post-He vessel welding), probe calibrations (Q_{ext}), etc.

Performance, while achieving required specifications, was inconsistent :

Problems dominated by FE (strength and onset) variability…

Average performance for first ~ 24 medium β cavities

Gradient at Q_o spec (MV/m) 11.0 (OK) Q_o at Operating Gradient 6 x 10^9 (~OK)

Maximum Gradient (MV/m) 12.0 (OK)   Field Emission Onset (MV/m) 8.3 (Bad)

Number of Tests to Qualify 1.9 (Very Bad!)

Improved Cavity Processing - Reduce FE

- Two reviews (Sep & Oct 2003) to identify process improvements
  - An internal review (S&T and assembly staff)
  - An external review, including management, cavity and process experts (4 involved directly in DESY effort)

- Identified process changes
  - Additional rinsing after chemistry and for HP rinsing
  - Keeping the cavity surface wet between chemistry and HPR steps
  - Allowing the cavity surface to dry between HPR steps
  - Adjust HPR head to increase the number of nozzles and reduce the nozzle diameter to increase impact force
  - Isolate cavities from test stand by evacuation in the cleanroom
  - Add flow thru rinsing during degreasing steps
  - Use fresh acid for all final processing (<10g/L Nb)
  - Remove more material after furnace treatment (100µm)

Medium β Cavity Results – Revised Procedures

Production testing resumed in October 2003, after revised processing and assembly procedures were implemented.

Performance was measurably improved!

Onset of FE delayed (but still large variability)… RF pulse-processing used to "destroy" early emitters, before "burn-in".

Average performance for remainder (11) of medium β cavities :

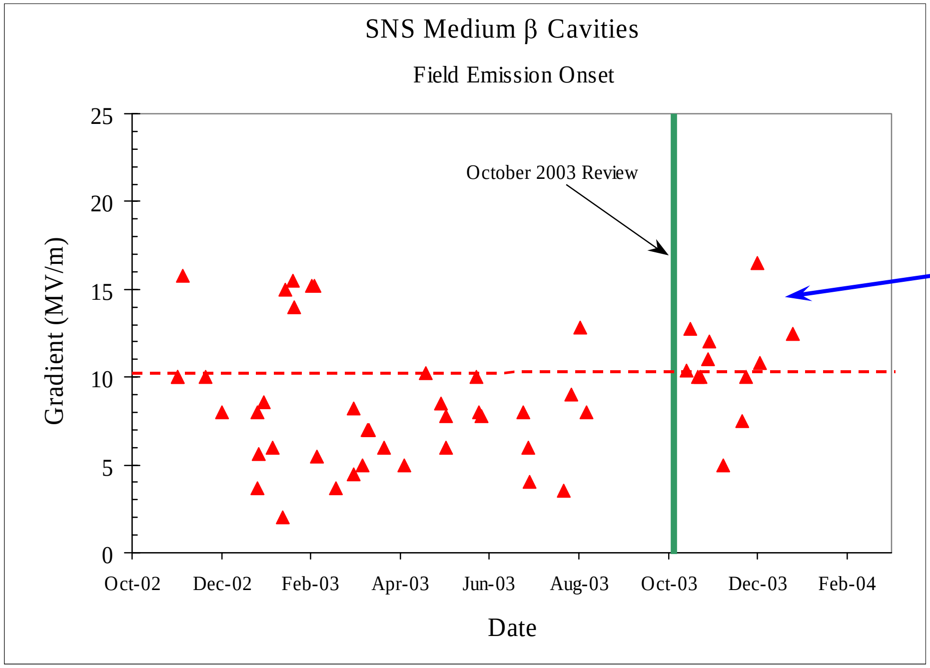
Gradient at Q_o spec (MV/m) 15.5 (!) Q_o at Operating Gradient 1.1 x 10^{10} (!)

Maximum Gradient (MV/m) 16.4 (!)   Field Emission Onset (MV/m) 10.7(Better)

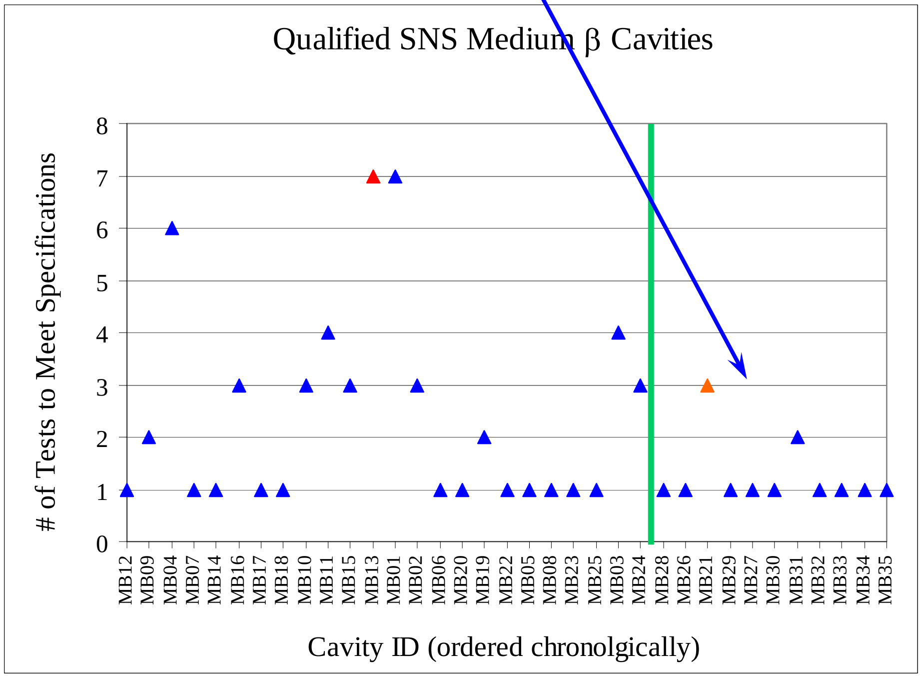
Number of Tests to Qualify 1.1 (Nice!)

Almost high β spec!

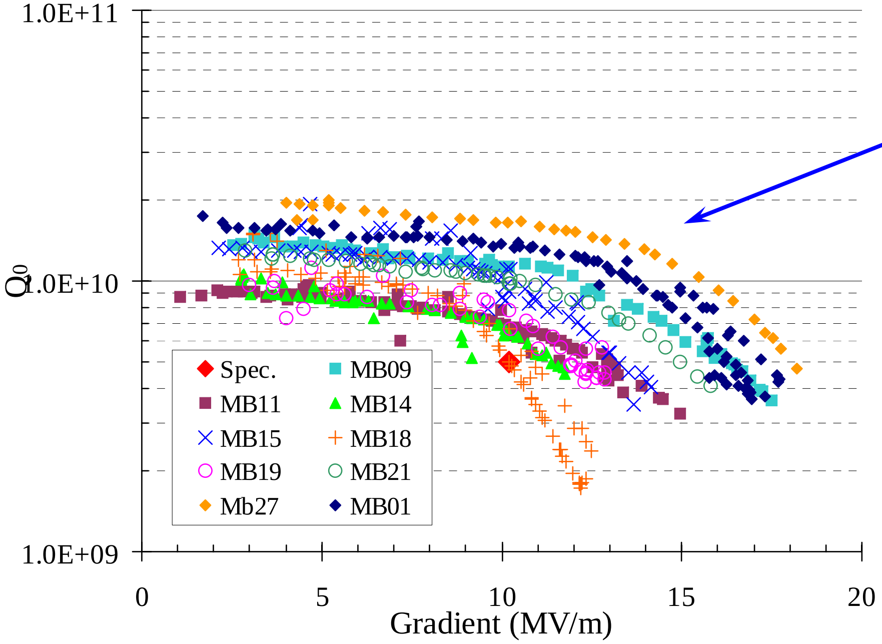
Medium β Cavity Results – Revised Procedures



Results after new procedures adopted

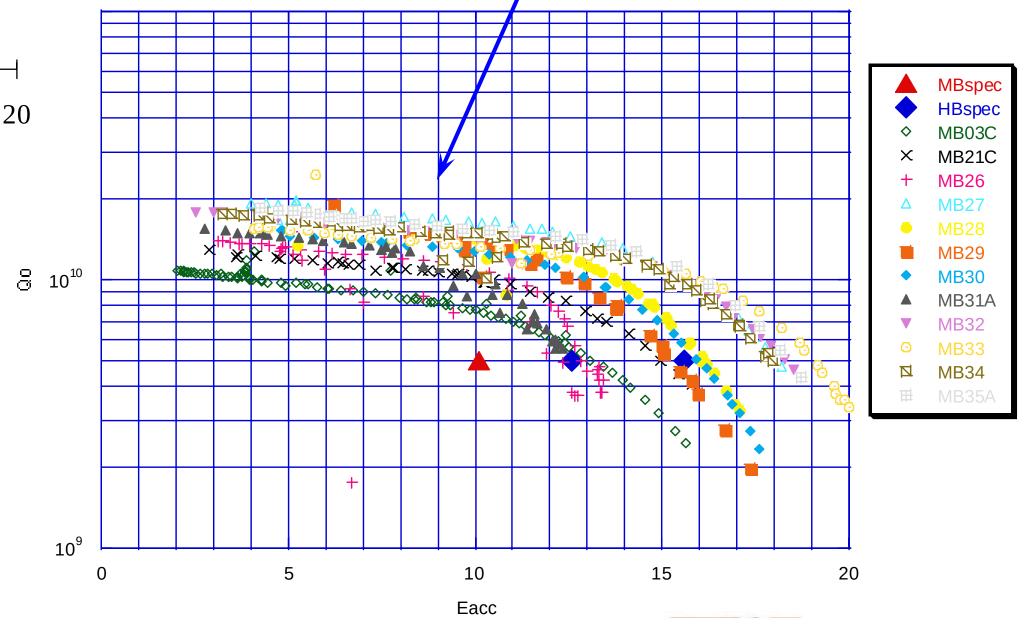


Medium β Cavity Results – Revised Procedures



Results **before** new procedures adopted

Results **after** new procedures adopted



High β Cavity Results

Production testing of the bulk of high β cavities began at the end of ‘03/beginning of ’04, upon completion of medium β cavity production testing. Identical (improved) processing/assembly procedures were used for high β as for medium β.

Field emission onset earlier… even with improved processes. Pulse-processing (developed in medium β testing) helped improve cavity test yield.

A new problem - Multipacting

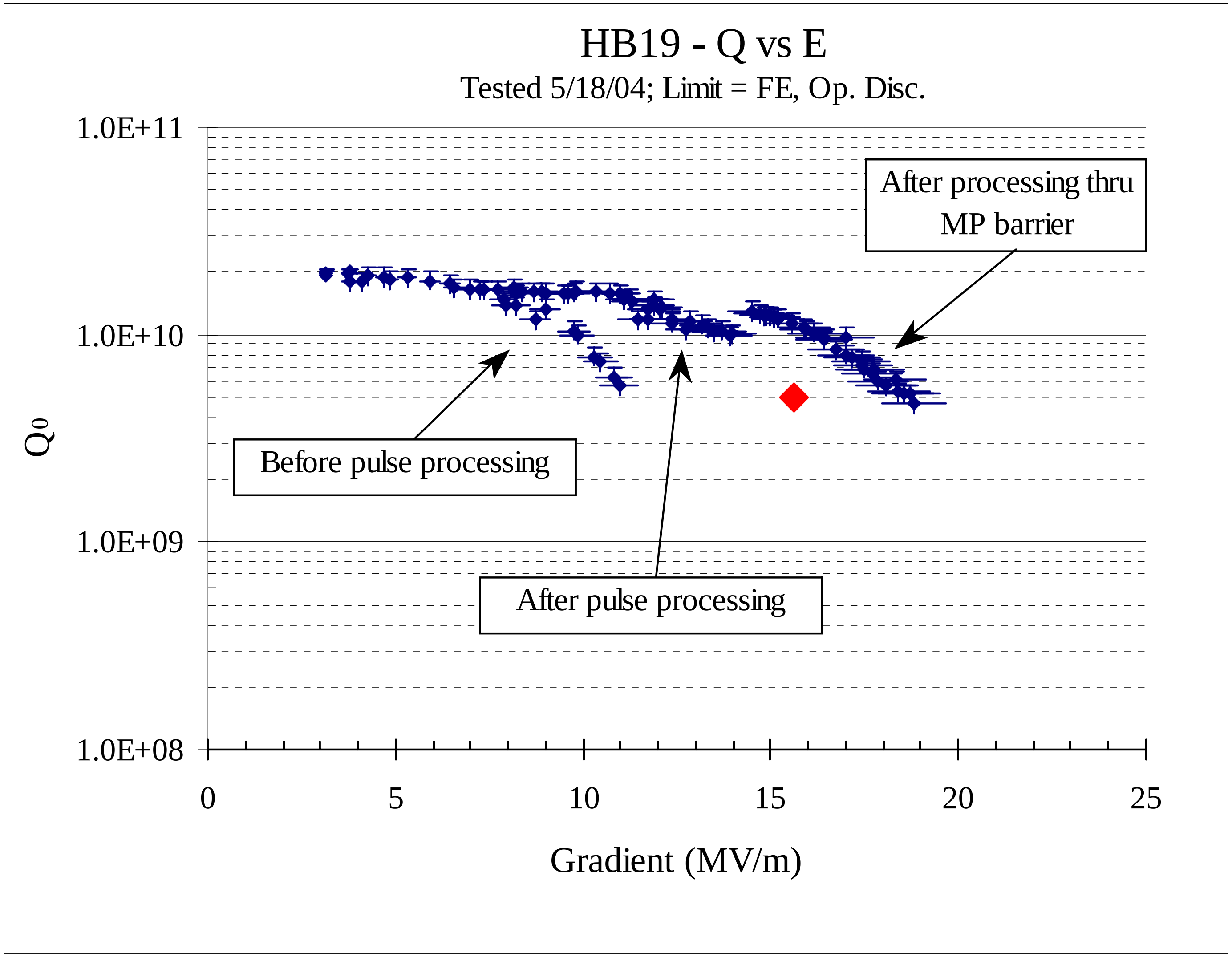
Average performance for 48 medium β cavities

Gradient at Q_o spec (MV/m) 15.8 (OK) Q_o at Operating Gradient 7 x 10^9 (~OK)

Maximum Gradient (MV/m) 15.9 (OK)   Field Emission Onset (MV/m) 5.9 (Bad)

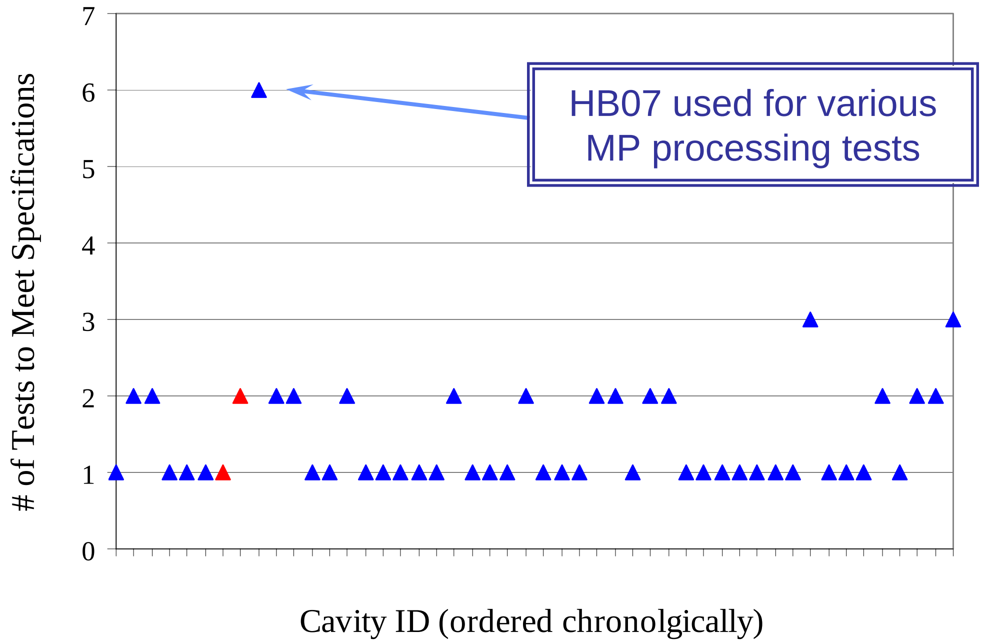
Number of Tests to Qualify 1.4 (Tolerable…)

High β Cavity Results

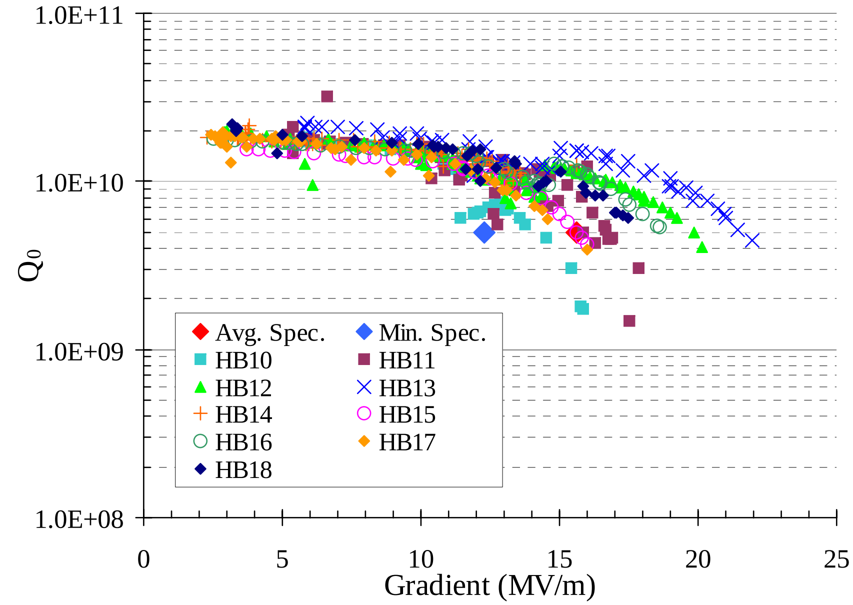


High β Cavity Results

Qualified SNS High β Cavities



Some typical Q vs E curves for SNS high β cavities



FE and Multipacting in High β Cavities

- **FE (radiation) onset appeared to occur at lower gradient than for the medium β cavities, but was generally successfully processed away quickly using pulsed RF processing. The phenomenology may be consistent with**
  - small emitters
  - localized emitter sites
  - low field MP barrier ? Without diagnostics (thermometry), impossible to differentiate from FE (though P_{trans} trace didn't exhibit typical MP behavior, and onset not consistent (as opposed to MP))

- **Multipacting was a dominant feature of SNS high β cavity performance, and appeared to be :**
  - Independent of pre-processing technique
  - Independent of active pumping/cavity isolation
  - Not predictably affected by He and/or Pulsed RF processing, or baking at 120° C

Summary of SNS Cavity Performance

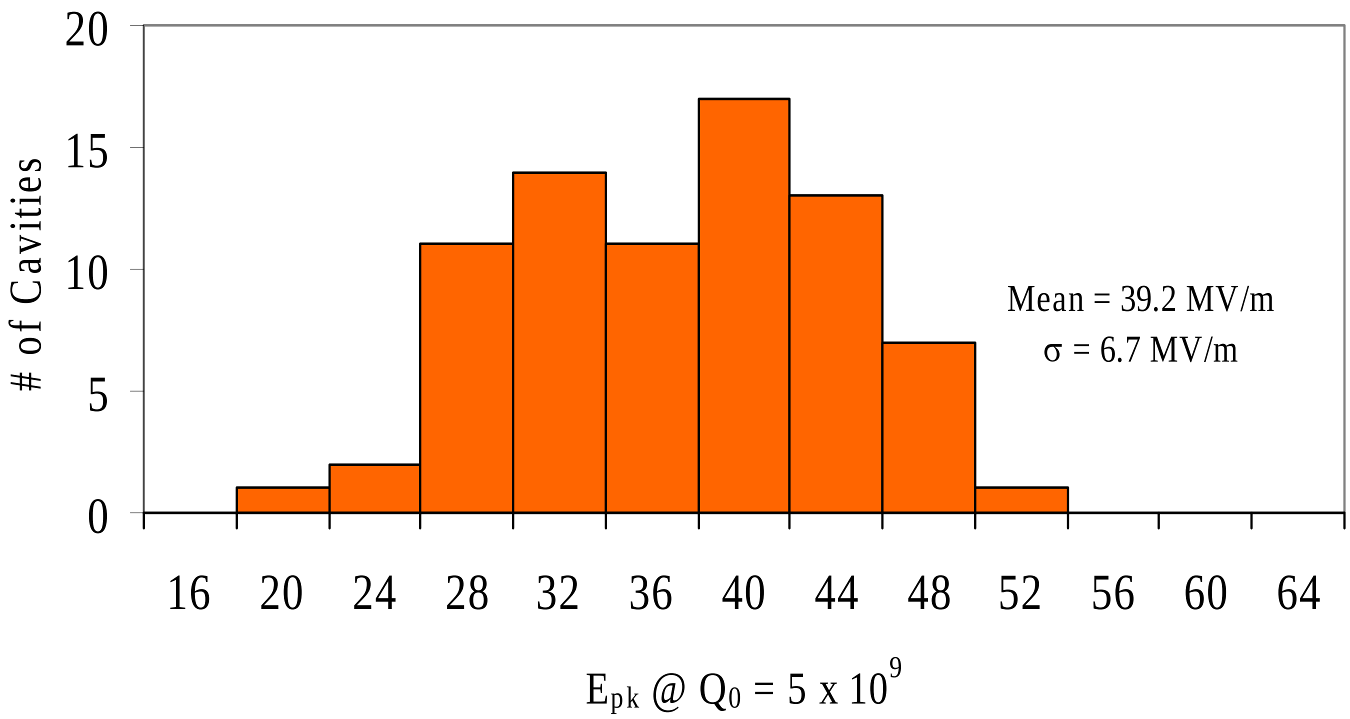
Average CW performance of all cavities that met specifications

Parameter	Medium β	High β
Gradient (E_{pk}) at Q_o spec (MV/m)	13.3 (36.0)	18.2 (39.9)
Maximum Gradient (E_{pk}) (MV/m)	14.3 (38.8)	18.7 (41.0)
Q_o at Operating Gradient	8.8×10^9	9.9×10^9
Field Emission Onset (MV/m)	9.7	6.2
Total number of cavities tested	35	48
Total number of tests (incl. non-qualification tests)	73	72

The above tests were performed in the span of ~ 2 years.

Summary of SNS Cavity Performance

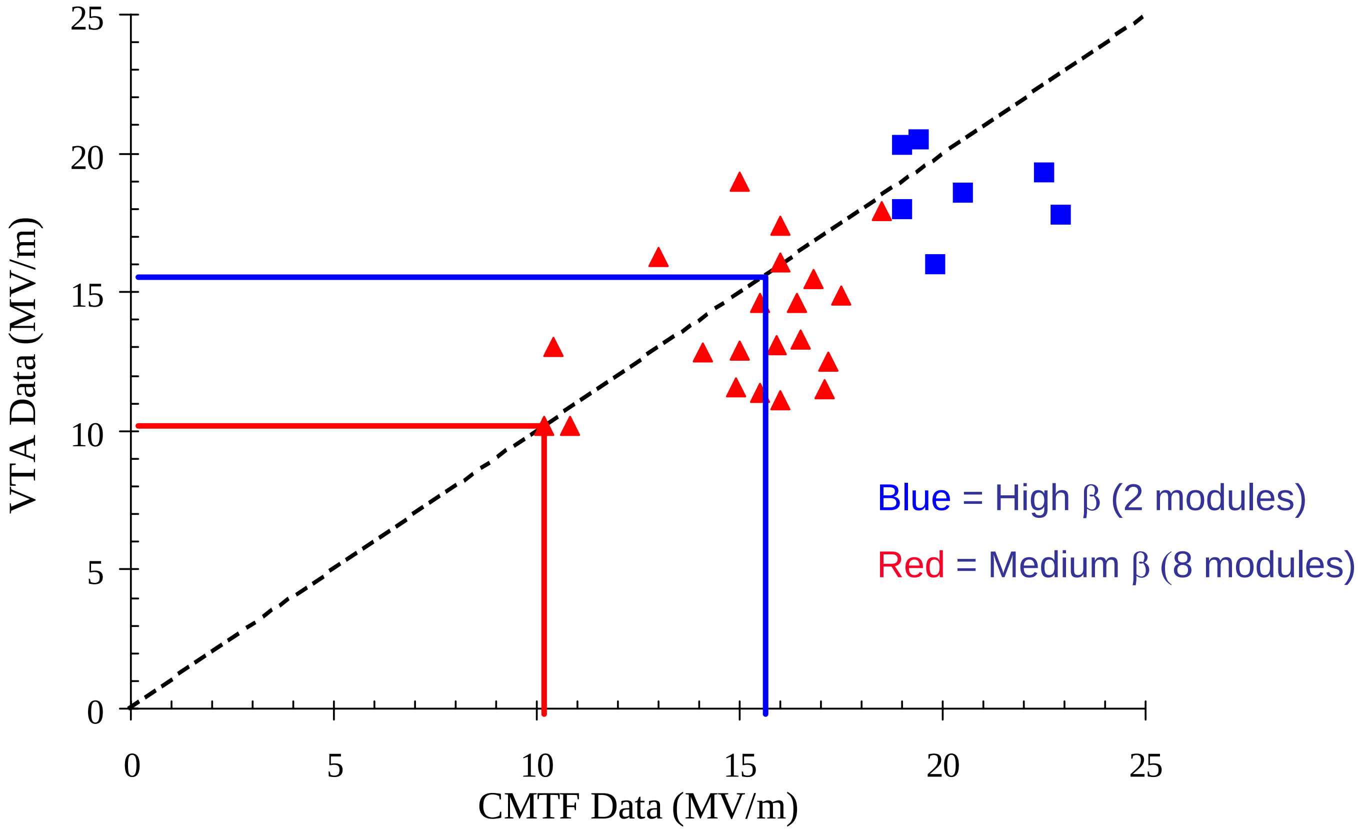
SNS Qualified Cavity Performance Distribution of
Peak Surface Fields



Comparison w/ Cryomodule Performance

Gradient at $Q_0 = 5 \times 10^9$

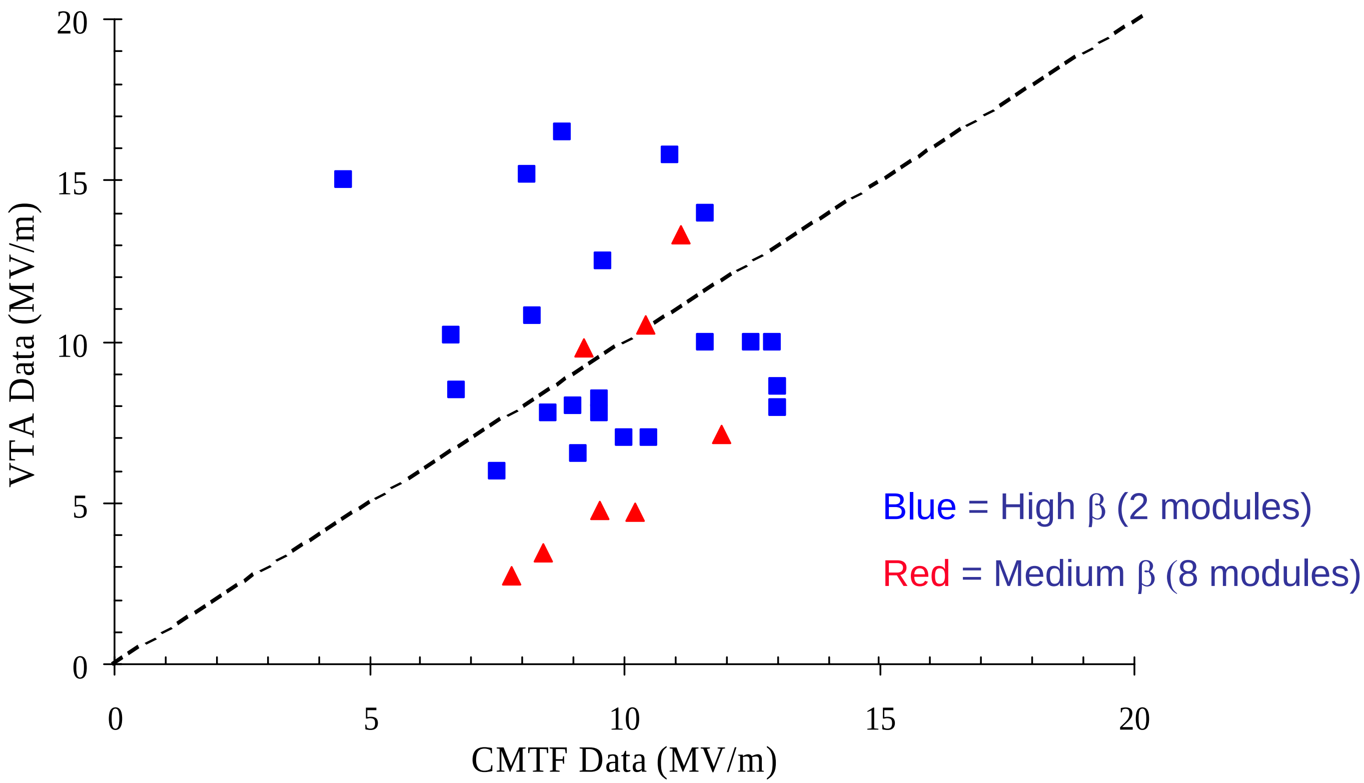
Cavity gradients in the CMTF were found to be ~35% higher than those measured in the VTA. This increase is perhaps due to the much lower RF duty factor (6-7%) employed during module testing. Note – no MP was ever observed in CM testing.



Comparison w/ Cryomodule Performance

Onset of Field Emission

No strong correlation exists. As FE onset is largely determined by environmental factors, and the cavities were re-processed before sting assembly, it is reasonable to conclude that vertical test FE onset is not a good predictor of onset of FE in a completed cryomodule.



Lessons Learned

In the prototype phase, process development & optimization is just as important as structure prototyping

- **Performance limited by FE**
  - ✓ **Procedure & process control**
  - ✓ **Contamination control**
  - ✓ **Process monitoring**
- **Inconsistent performance**
  - ✓ **Documented procedures**
  - ✓ **Personnel training**
  - ✓ **Personnel continuity**

Crucial to ALL SRF cavity projects

- **Earlier FE onset in high β cavities using identical procedures/processes/personnel remains a mystery.**

Lessons Learned

Evaluate & optimize facilities for applicability to particular design or process

- Reduced effectiveness of HPR system
  - ✓ Larger cavity equator and iris radii – reduced impact energy
  - ✓ Larger cavity surface area – reduced coverage
  - ✓ Cell shape (β<1) - lower momentum transfer as $\theta_{norm} \neq 0$
  - ✓ Cavity weight → component wear and failures
- HPR pump failures
  - ✓ Original pump not designed for continuous use
  - ✓ Additional rinsing → motor lifetime impact, H_2O capacity limitations
  - ✓ Replacement (spare) pumps not identical (grease)
- Additional process monitoring
  - ✓ Particle counts (air, HPR water)
  - ✓ TOC monitoring
  - ✓ RGA scan for hydrocarbons during cavity pumpdown

Lessons Learned

Multipacting codes provide only general guidance…

- MP potential predicted for both cavity types
  - ✓ Only observed in high β cavities
  - ✓ Cavity surfaces should be similar
  - ✓ Low prototype statistics (some high β production cavities also did not show MP)

- For β<1 shapes, greater potential for MP
  - ✓ Confirmation on (multiple) prototypes important
  - ✓ Surface treatment more critical
  - ✓ Higher temperature baking or other recipes may need to be developed

Lessons Learned

Guiding Principles for production-scale SRF implementations…

- Prototype program must be comprehensive.
- Consider a pre-production phase.
- Personnel continuity, discipline, and training key to performance.
- Facilities must be matched to design/process specifics.
- Module performance may only be weakly coupled to vertical cavity performance if significant handling occurs in between… so minimize it, or control & monitor it explicitly.
- Quality control measures are important throughout every dimension of the process, with timely and frequent feedback required. Everything matters… this is difficult work!

Acknowledgments

The production testing of the SNS cavities was a significant undertaking that required the dedicated efforts of many people, representing various disciplines, in several departments and groups, over a several year period.

They did a great job, and we learned much.