State of the Art of Multicell Superconducting Cavities and Perspectives*

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Topics

- **Some SRF basics**
- **Cavity Design Considerations**
- **Technology Improvements**
- **Experimental Results**

Applications

SRF Technology is becoming increasingly attractive to accelerator labs for new projects or plans. This is because of a maturing of the technology.

- **SCA, Tristan, LEP, HERA, CEBAF**
- **Colliders: TESLA, muon-collider**
- **B – factories (Cornell, KEK), Light sources (Taiwan, Canadian)**
- **Proton machines: SNS, ESS, JAERI/KEK Joint Project, Trasco, ASH, LANL(AAA)**
- **ERL's, FEL's**
- **Heavy Ion Accelerators, RIA**

Why SRF?

- CW operation or long pulse operation because of low losses
- Better beam quality: energy stability, energy spread, emittance
- Higher availability because of reserve capabilities of the cavities
- Upgrade potential as technology improves

For application in proton linacs such as SNS:

- UHV from cryo-system creates less beam-gas scattering
- Large aperture of sc cavities reduces linac component activation due to beam loss

Accelerating Cavity

- Typical accelerating cavity is excited in TM_{010} mode

- Longitudinal E –fields have a phase shift of 180° between adjacent irises; a particle with β = 1 will experience the maximum acceleration in each cell

- Q – value

$$Q_o = W/(P_{cav} /\omega)$$

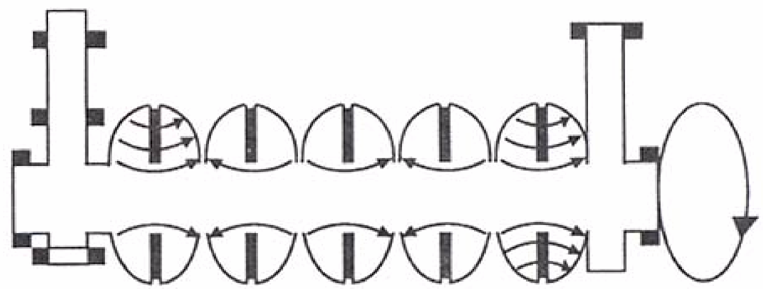
W = Stored Energy, P_{cav} = dissipated power in cavity walls

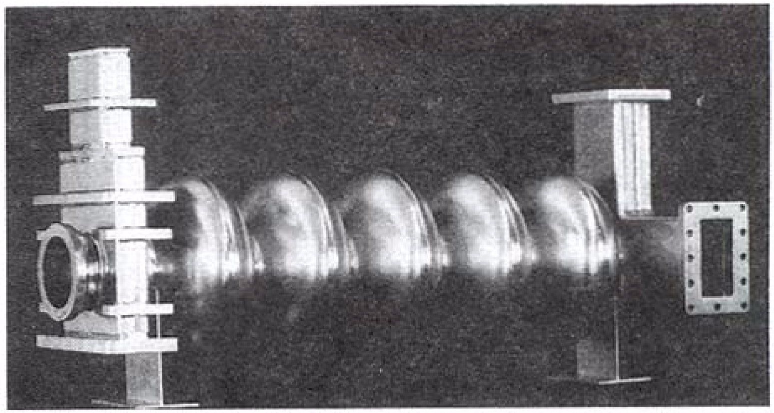
$$Q_o = G / R$$

R = Surface Resistance, G = Geometry factor ~ 270 Ω

- Accelerating gradient

$$E_{acc} = k (PQ_o)^{1/2}$$





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T – Dependence of Surface Resistance

- In the superconducting state an external magnetic field penetrates only a distance of λ (f, T, l) into the material: ~600 Å at $T < 0.9\ T_C$ ($T_C = 9.25K$ for Nb)

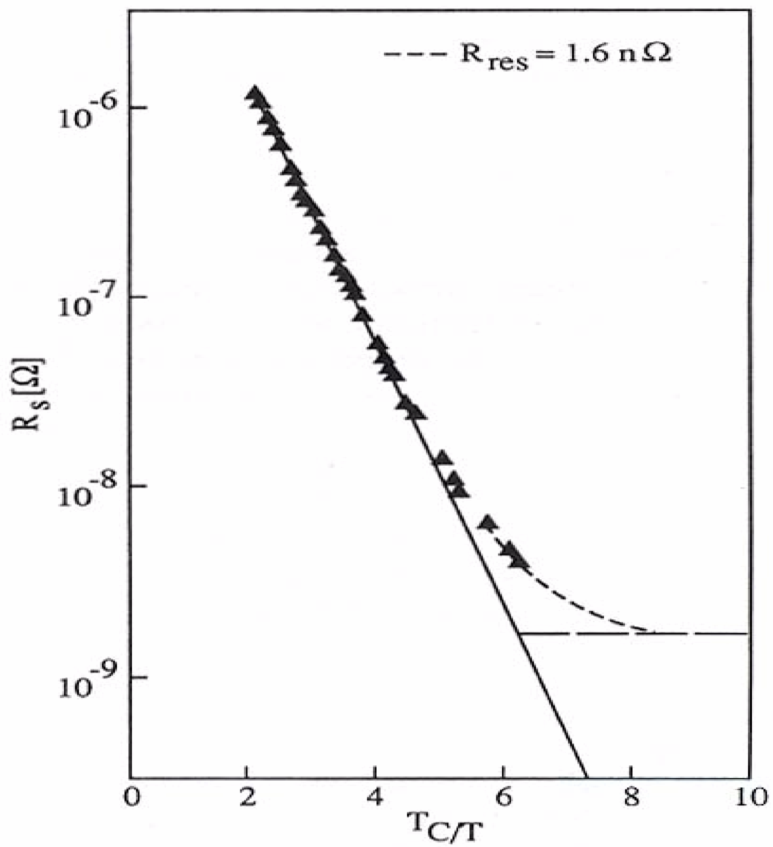
- Losses described by a surface resistance take place in a very thin surface layer

- BCS theory

$$R_{BCS} \sim (\omega^2/T)\ \exp(-\ [(\Delta/kT_C)(T/T_C\ )$$

- In reality there is a residual resistance

$$R\ (T) = R_{BCS} + R_{RES}$$



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Deviations

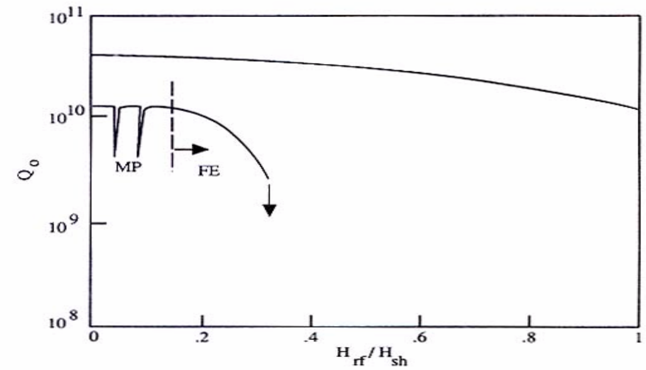
- Observed Q-value lower due to
  Residual Surface Resistance
  caused by anomalous losses and defects

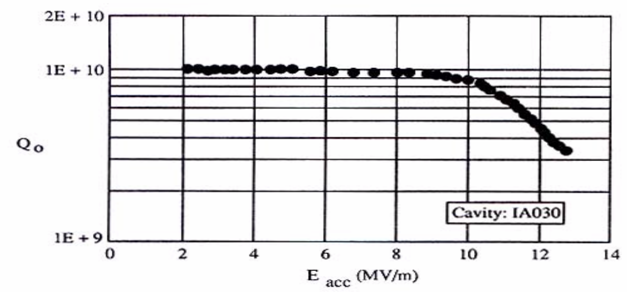
- Resonant Electron Loading ("Multipacting") causes Q-drops and barriers

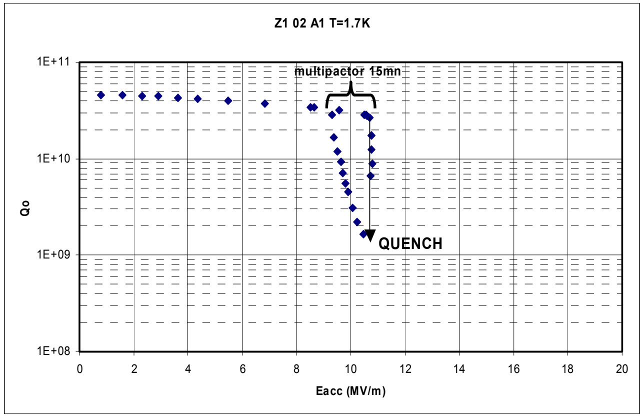
- Exponential decrease of Q-value at higher gradients due to
  Non-Resonant Electron Loading
  (Field Emission) caused by contamination

- "Quench" field levels are below H_{SH}

  $0.1\ H_{SH} < H_{RF} < 0.5\ H_{SH}$







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Residual Resistance

Properties

- Temperature independent
- Proportional to f^2 on the same surface, independent in different cavities
- localized or "patchy"
- Varies widely with surface preparation
- as low as 1 nΩ, typically

  $5\ n\Omega < R_{res} < 30\ n\Omega$
- Lower after heat treatment in UHV at $T > 800\ ^0C$

Contributions

- Dielectric losses such as gases, chemicals, adsorbates, dust
- Normal conducting defects (e.g., foreign material inclusions)
- Surface imperfections such as cracks, scratches, delaminations
- frozen-in magnetic flux from ambient fields: ~ 0.3 nΩ/ mG
- Hydride precipitation (" Q-disease")
- Large density of localized electron states exists in highly disordered metal-oxide interface: can lead to absoprtion of photons

Multipacting (1)

- Multipacting is a high vacuum avalanche effect initiated by emission of secondary electrons in response to impinging primary electrons

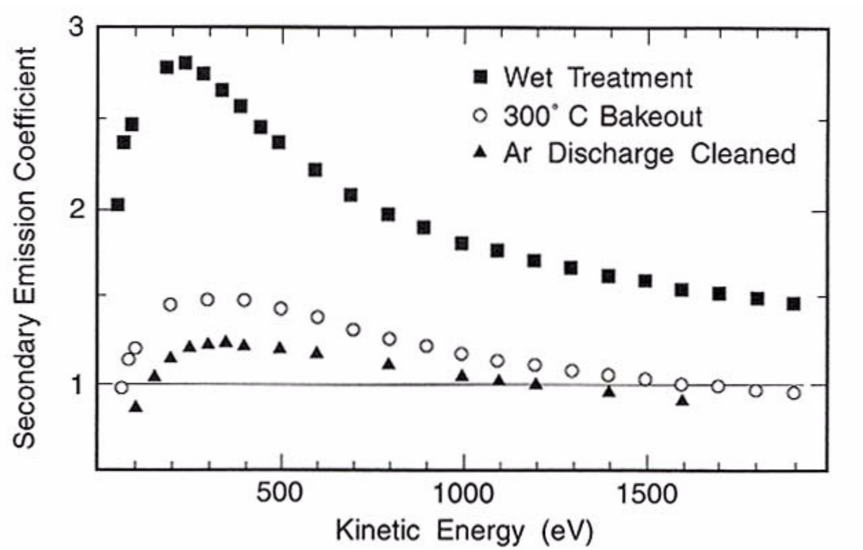
- Certain conditions have to be satisfied to generate multipacting:

  - An electron emitted from a cavity wall is under the influence of the EM fields returning to its origin within an integer number of half an rf cycles

  - The impacting electrons produce more than one electron, if the impact energy is high enough

- For niobium this is the case for
  $50\ eV < E_{imp} < 2000\ eV$

- The SEE is very sensitive to surface conditions

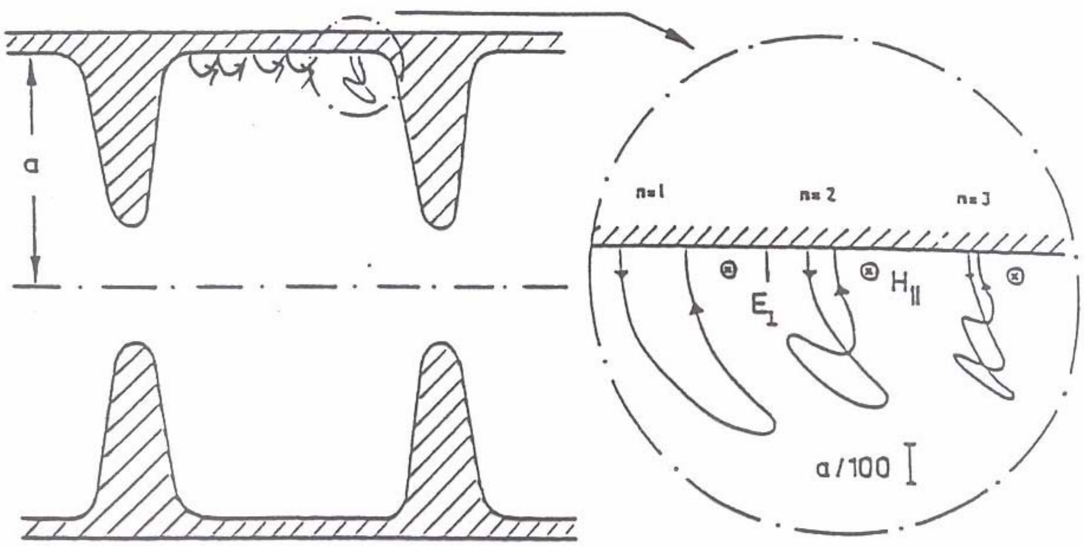


Multipacting (2)

One-point Multipacting

Typical cylindrical symmetric accelerating cavity

- small $E_{perpendicular}$
- Gradient in $E_{perpendicular}$
- uniform H_{par}



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Multipacting (3)

Suppression of Multipacting by geometrical changes in the cavity shape to spherical or elliptical cross sections:

- larger E_{perp} at outer wall
- larger excursions of electrons into cavity volume
- electrons step out of phase with rf and gain less energy
- E_{imp} is too small for SEE > 1

Multipacting presents today no serious problems anymore; however, carelessness in degree of surface contamination is dangerous

Field Emission (1)

Observations

- Field Emission is coming from point-like sources
- FE current can be described by a modified Fowler-Nordheim equation

$$\mathbf{I = A \times S \times (\beta E)^{2.5} \times 1/\Phi \times \exp -\{(B \times \Phi^{1.5})/(\beta E)\}}$$

$2500 < \beta E < 15000$ $10^{-4}\,cm^2 < S < 10^{-12} cm^2$

- β is independent of frequency
- Emitter density depends strongly on processing and handling
- FE sensitive to adsorbates, gas exposure, chemical residue, particulate contamination
- FE behavior can be influenced by "processing": high peak power, helium

Field Emission (2)

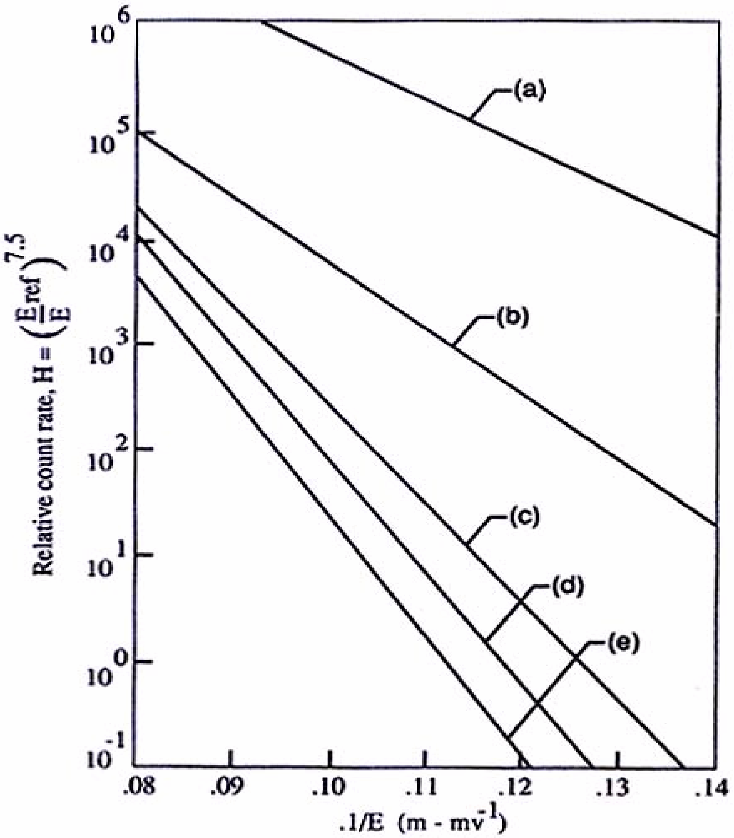
He – **processing**:

- Cavity is operated with a partial pressure of He inside (~ 10^{-4} torr) in the FE regime

- Ionized He will bombard the surface and reduce field emission current

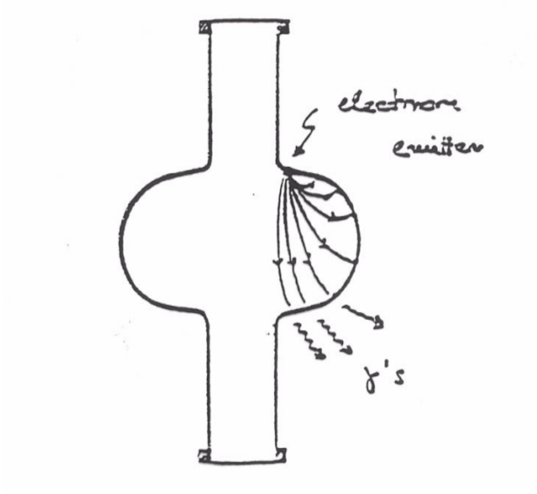
Fowler-Nordheim Plots

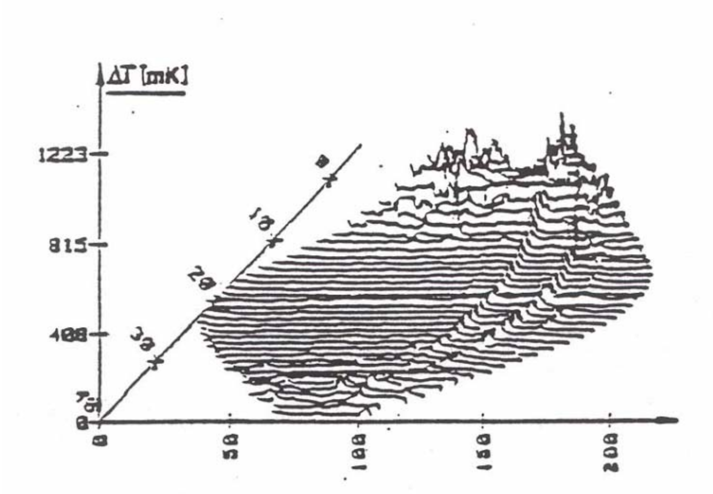
(H.A.Schwettman et al., JAP 45,914 (1974)



Field Emission (3)

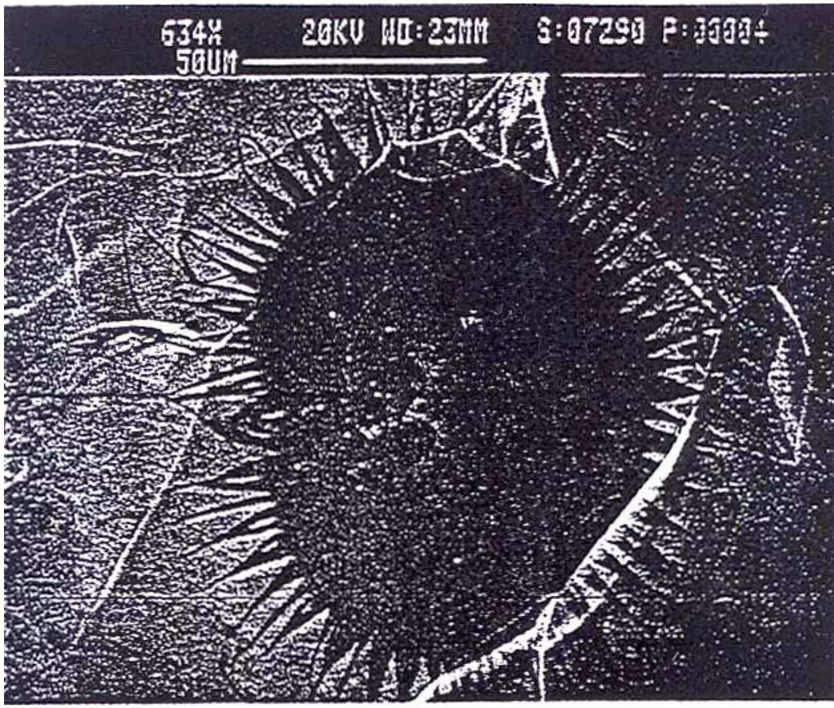
Temperature map of trajectories from a point–like emitter in a 500 MHz single cell cavity tested at CERN

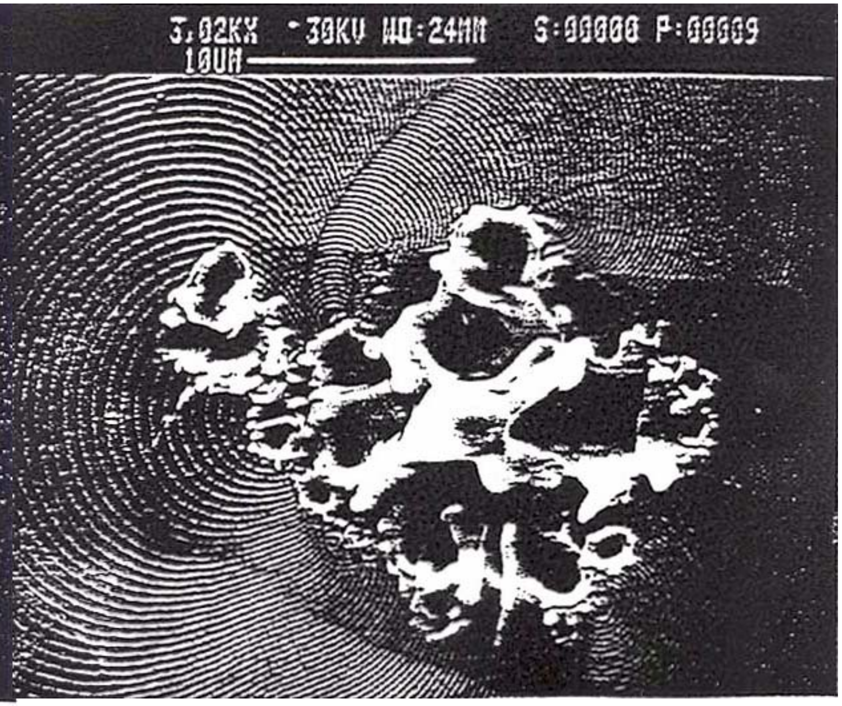




Field Emission (4)

Pictures taken at Cornell University





Defects/"Quench" (1)

- Thermal instabilities occur at localized "defects" with higher resistance than their surroundings:
  - chemical residue, debris, dust, areas of weak superconductivity
  - holes, scratches, weld splatter, delaminations
- Thermal model calculations done at various labs (HEPL, Cornell, CERN, Univ. of Wuppertal) indicate that thermal stabilization is achieved through improvement of the thermal conductivity of the niobium
- The achievable quench field is proportional to

$$H_q \sim \sqrt{\kappa(T) / r_d R_d}$$

$\kappa(T)$ = thermal conductivity, r_d = defect radius, R_d = resistivity of defect

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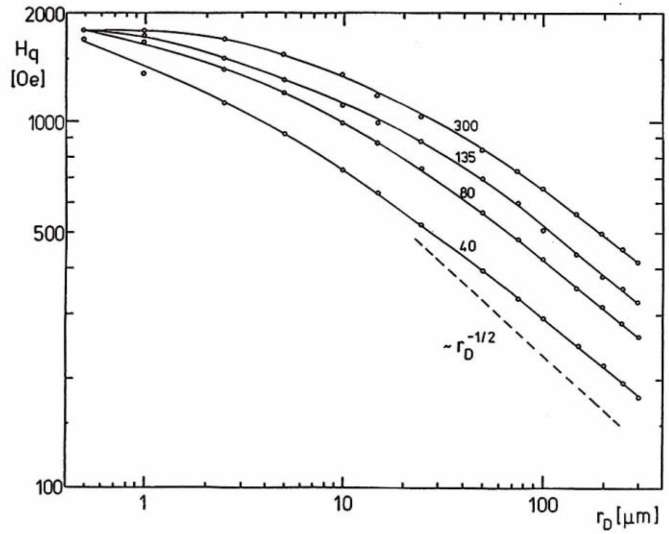
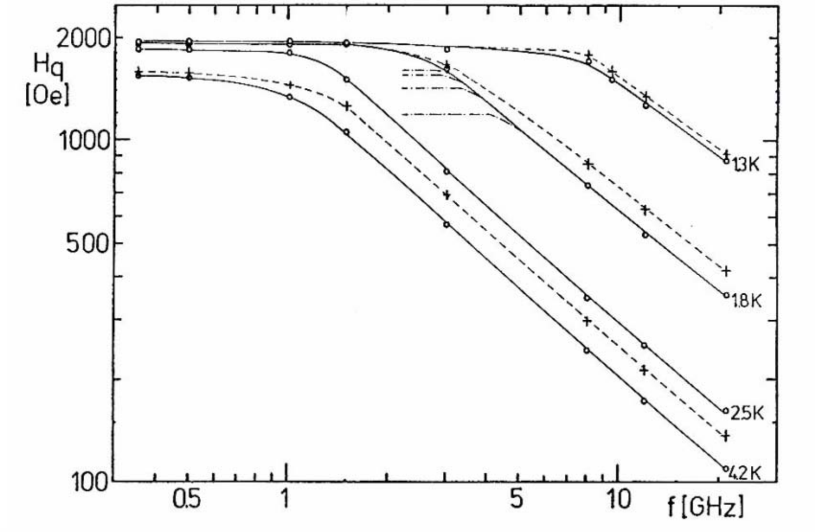
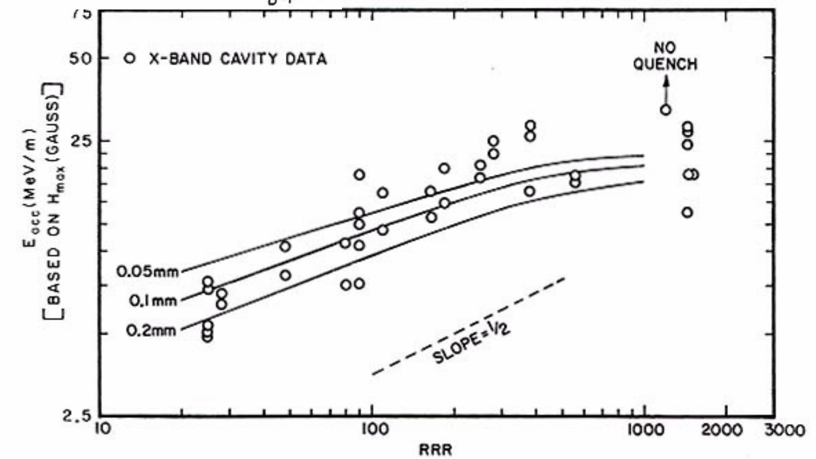
Defects/"Quench" (2)

Dependence on defect size
for different RRR values, f= 3 GHz

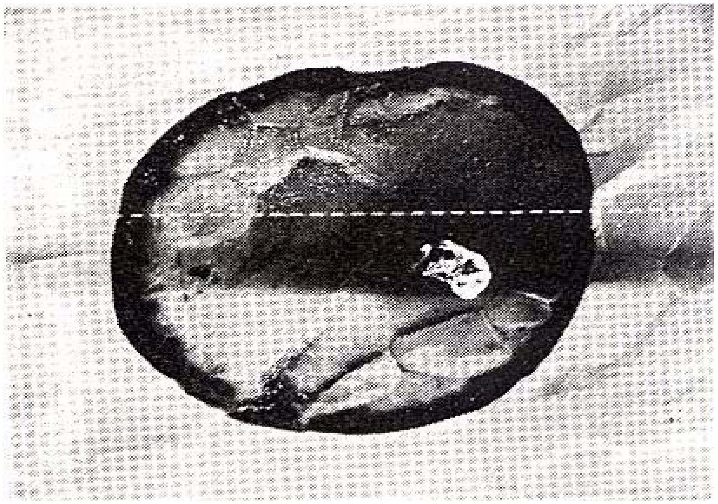


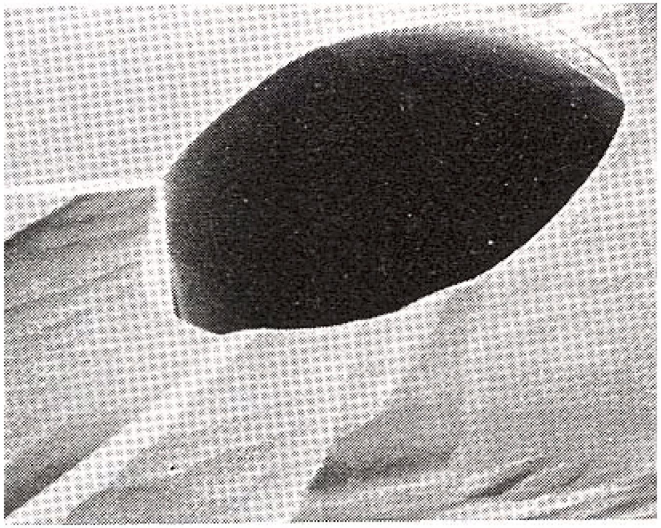
Defect-free case

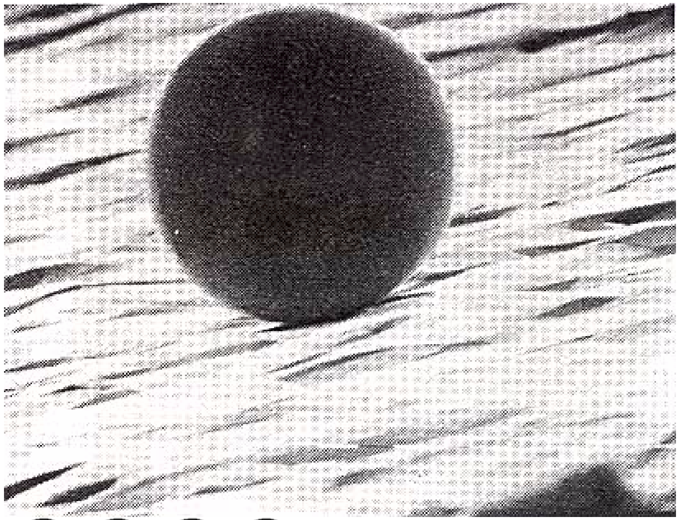


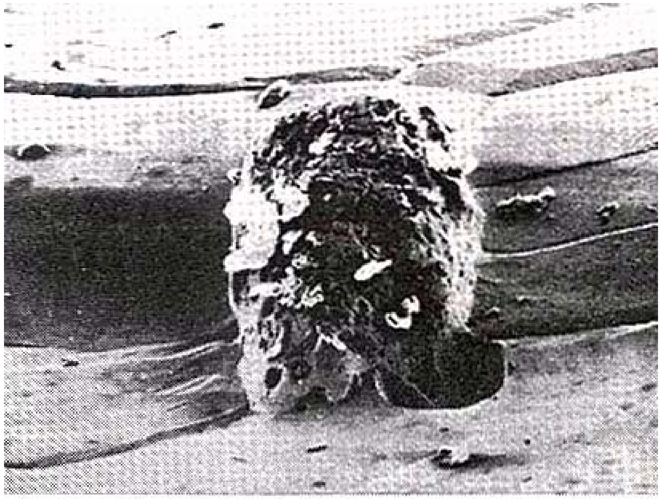


Defects/"Quench" (3)









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References

Good references for SRF technology issues are:

- " RF Superconductivity for Accelerators"
  H. Padamsee, J. Knobloch, T. Hays

- Proceedings of the Workshops on RF Superconductivity 1981 to 2001

- Poster Session T 07

Cavity Design Considerations (1)

- Electromagnetic Design: Do I want to optimize the cavity for, e.g., high gradient or low losses?
  - Peak Surface Electric Fields (for SNS $E_{peak} < 27.5$ MV/m)
  - Peak Surface Magnetic Fields (for SNS $H_{peak} \leq 60$ mT)
  - Shunt Impedance: influences the cavity losses
  - Number of cells N and cell-to-cell coupling factor k:

    influences peak fields and sensitivity to mechanical tolerances
  - Inclination of side walls α: influences mechanical rigidity
  - Lorentz force detuning coefficient: determined by rf control system issues, influences choice of material thickness and need for stiffeners

Cavity Design Considerations (2)

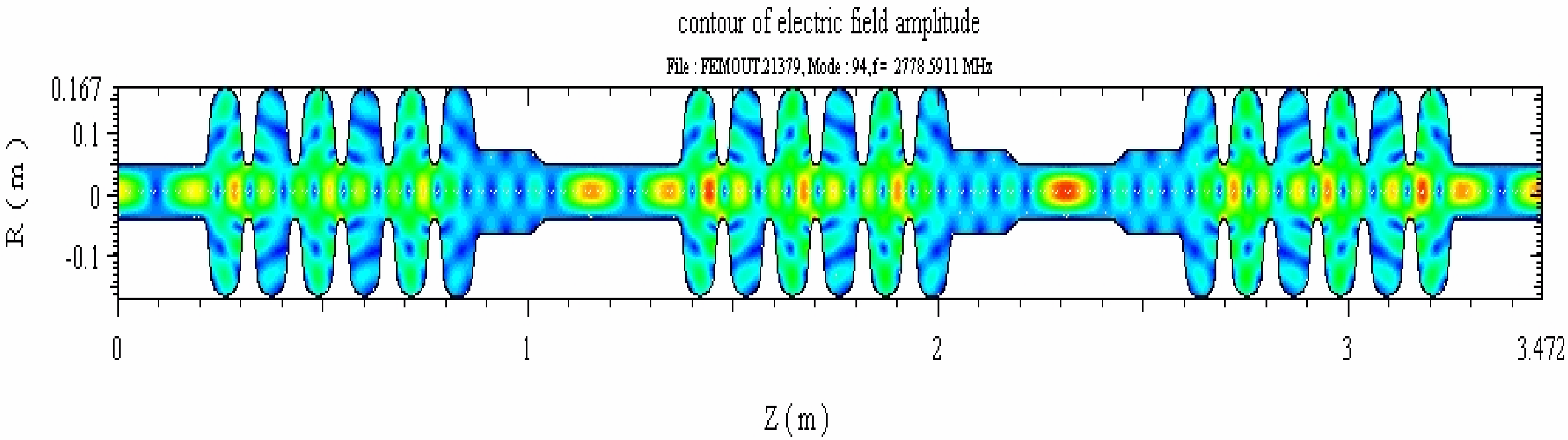
- Q_{ext} of Input coupler: is determined by beam dynamics, influences the size of the beam pipe, the location of the ports and the penetration of the center conductor

- Higher Order Mode damping: requirements set by beam stability criteria and shunt impedances of dangerous modes, they determine the location, orientation and number of HOM dampers

- Higher order modes are not always only located in the cavities, but can also exist in connections between cavities: therefore it is crucial to calculate HOM patterns not only in the cavities but also in the whole string for a cryomodule

Cavity Design Considerations (3)

HOM at 2778 MHz in SNS beta = 0.61 Cryomodule (J. Sekutowicz)



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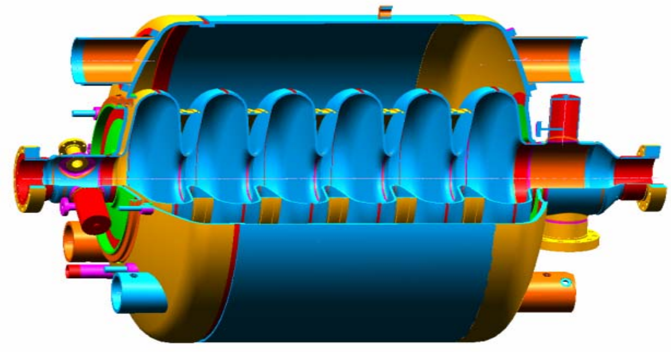
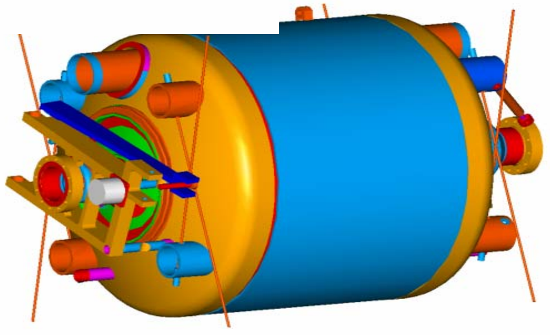
Cavity Design Considerations (4)

Cryostat

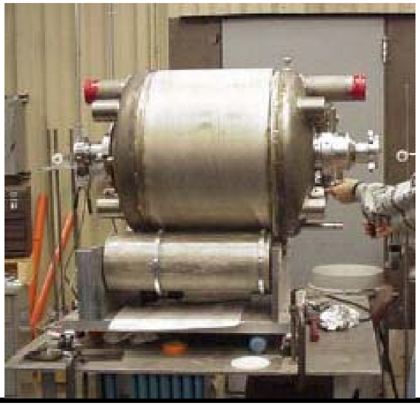


- Typically the helium vessel is an integral part of the cavity



- The volume is determined by the losses in the cavity at the operating temperature and gradient

- Material (Ti, NbTi, SS) influences stiffness, microphonics and requirements for tuner

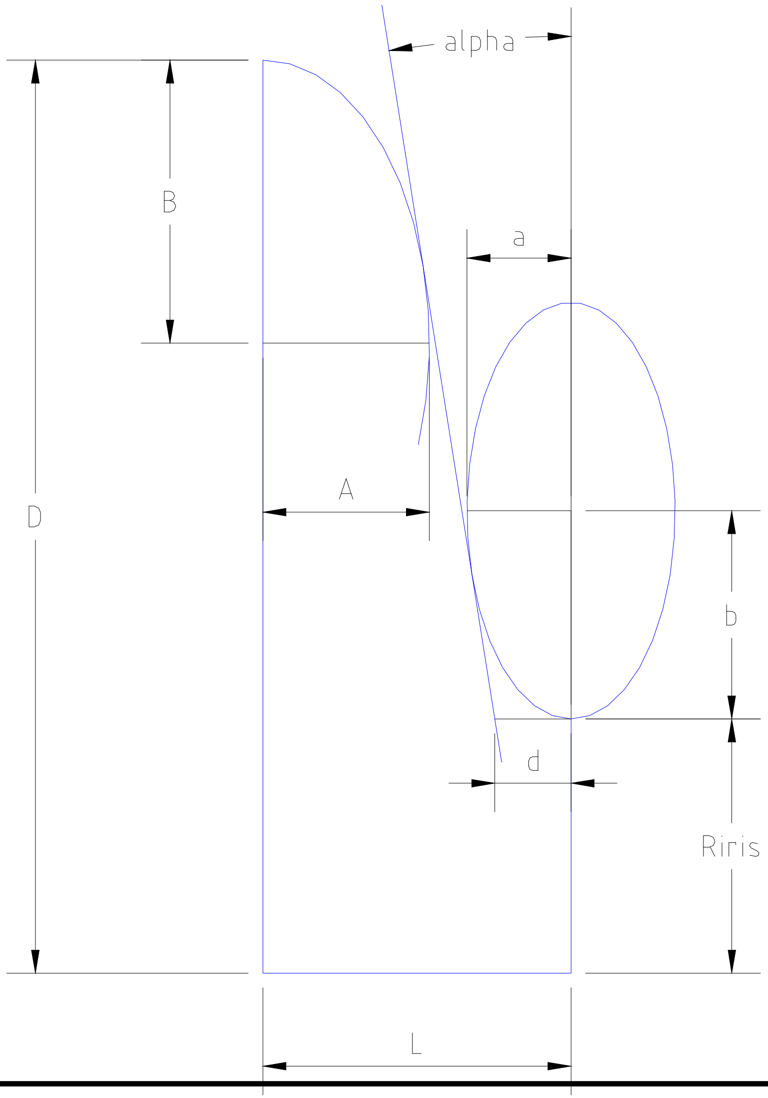


Cavity Design / Cell Shape (1)

Full parametric model of the cavity in terms of 7 meaningful geometrical parameters:

- ✓ Ellipse ratio at the equator (R=B/A)
  ruled by mechanics
- ✓ Ellipse ratio at the iris (r=b/a)
  Epeak
- ✓ Side wall inclination (α)
  and position (d)
  Epeak vs. Bpeak tradeoff and coupling k
- ✓ Cavity iris radius Riris
  coupling k
- ✓ Cavity Length L
  β
- ✓ Cavity radius D
  used for frequency tuning

Behavior of all e.m. and mechanical properties has been found as a function of the above parameters



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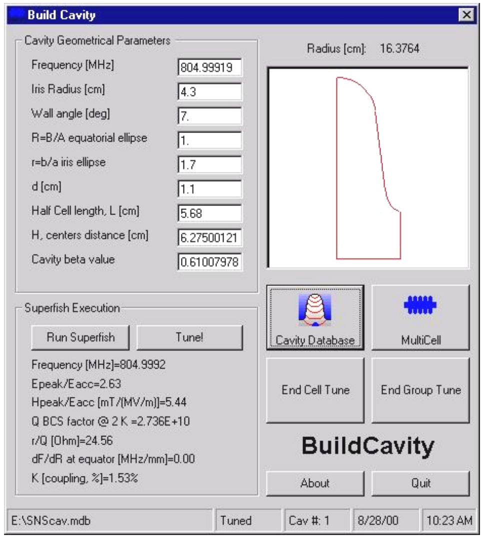
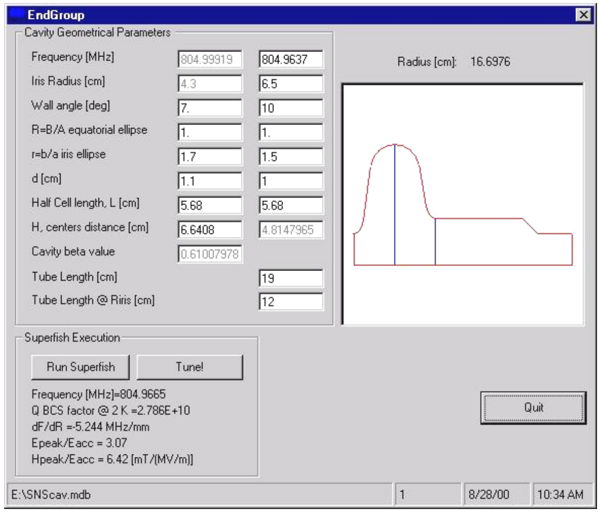
Cavity Design (2)

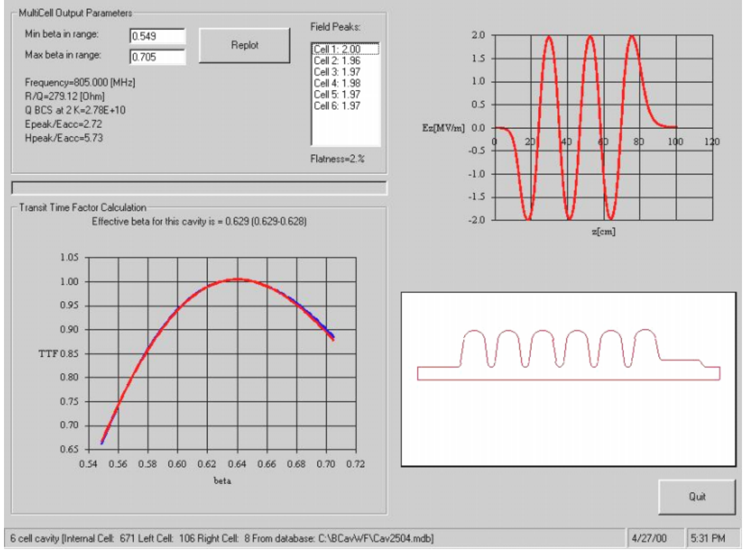
Parametric tool BuildCavity developed at *INFN Milano* for electromagnetic cavity design (C. Pagani et al.; 10th SRF Workshop):

- All RF computations are handled by SUPERFISH
- Inner cell tuning is performed through the cell diameter, all the characteristic cell parameters stay constant: R, r, α, d, L, Riris
- End cell tuning is performed through the wall angle inclination, α, or distance, d.

  R, L and Riris are independently settable.
- Multicell cavity is then built to minimize the field unflatness, compute the effective β and the final cavity performances.
- A proper file to transfer the cavity geometry to ANSYS is then generated



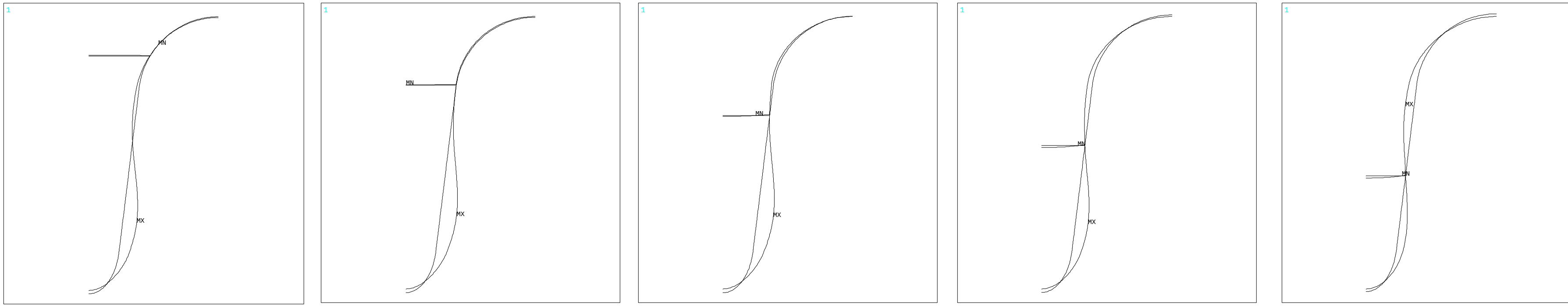


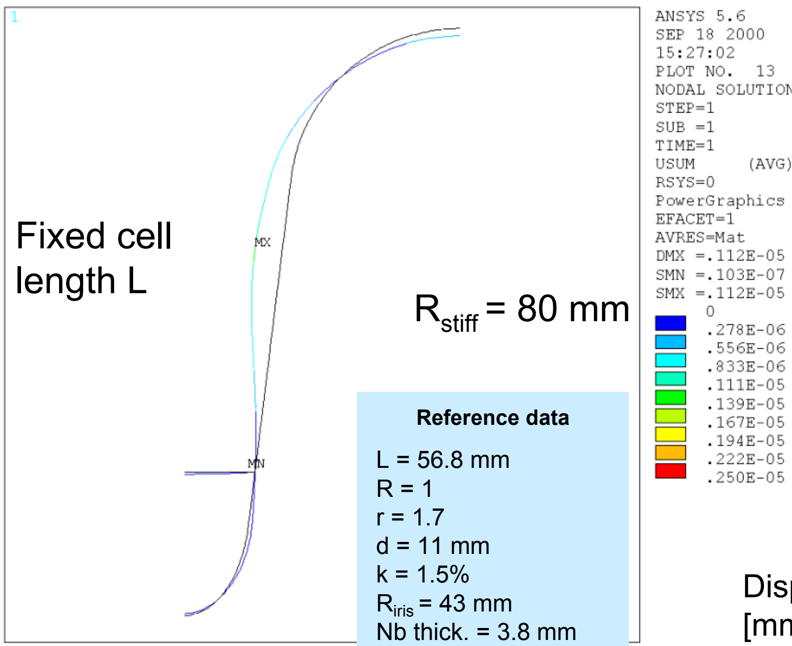


Inner cell data

L = 56.8 mm
R = 1
r = 1.7
α = 7°
d = 11 mm
R_{iris} = 43 mm

Cavity Design/ Stiffening Ring (3)



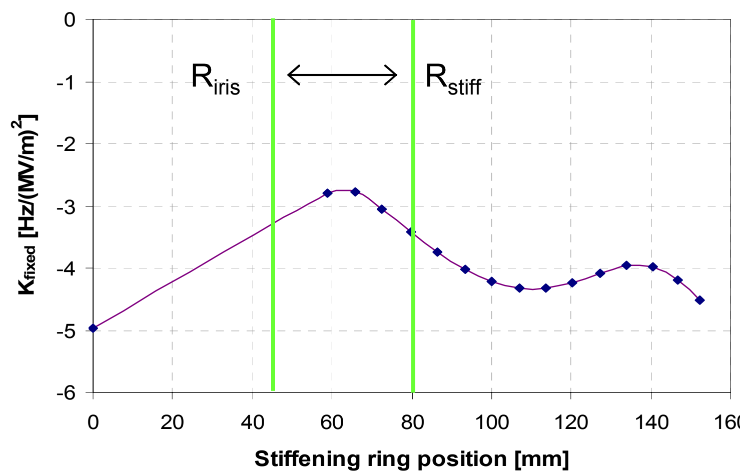


Reference data

L = 56.8 mm
R = 1
r = 1.7
d = 11 mm
k = 1.5%
R_{iris} = 43 mm
Nb thick. = 3.8 mm

Displacements [mm]

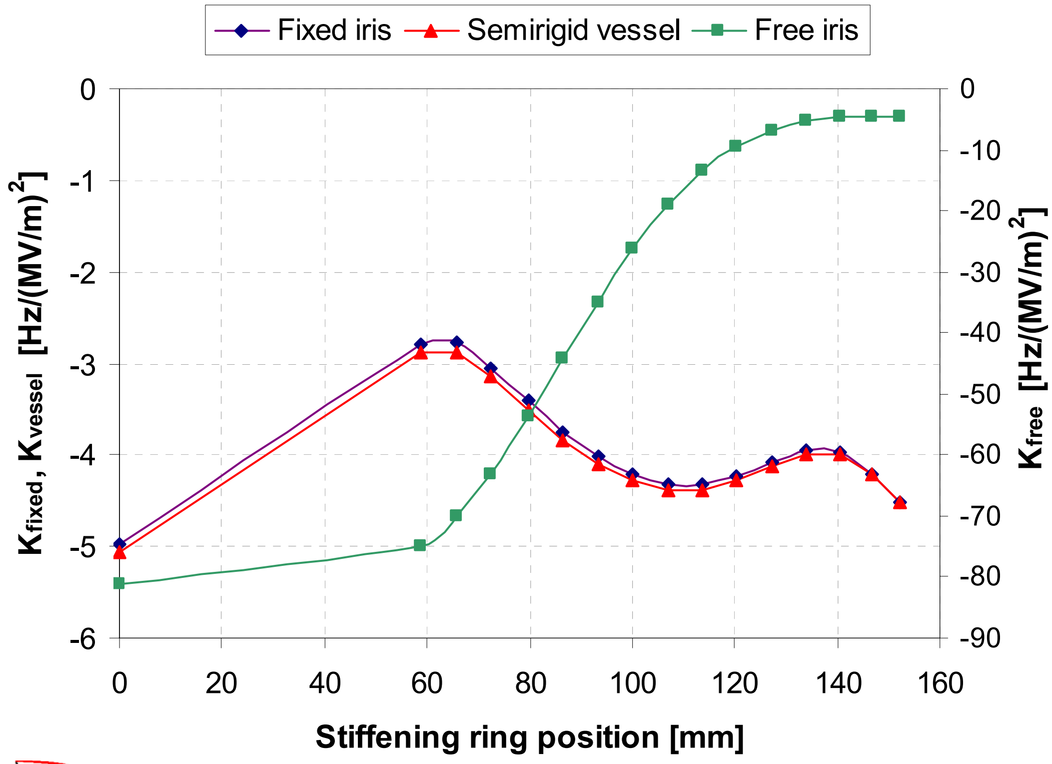
The Lorentz forces coefficients for 15 different stiffening ring positions are evaluated automatically with ANSYS, preparing the geometry and reading the fields from the SFO output from SUPERFISH



Cavity Design/Lorentz Force (4)

The estimate for KL strongly depends on the cell boundaries. For the SNS cavities 3 different cases were considered:

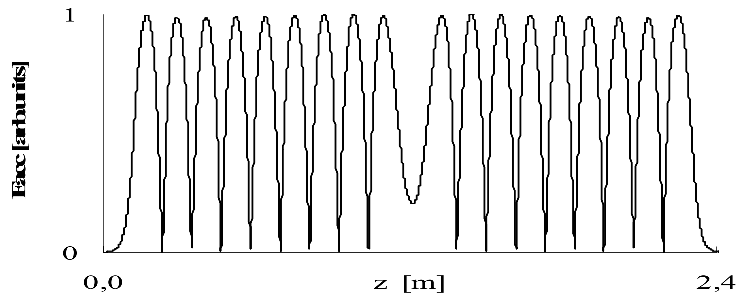
- Fixed cell length
- Free cell length
- Helium Vessel/Tuning System (= 3 tubes with diameter 30 mm and thickness 2 mm)

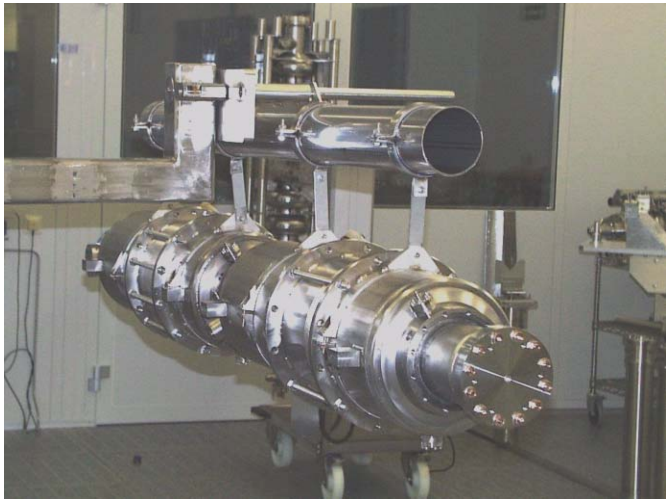


Superstructure

Superstructure idea developed by J. Sekutowicz at DESY (Phys.Rev.STAB 1993)

- Two 9-cell cavities are connected by a larger diameter beam pipe of λ/2 length to form a weakly- coupled 18-cell structure
- 2 HOM couplers at the interconnecting pipe and one at each cavity end provide sufficient HOM damping below BBU limit
- Each sub-unit has integrated He – vessel and tuner
- Structure is 2.38 m long and is fabricated and treated as one unit
- Major cost reduction due to less couplers
- Test is underway at DESY



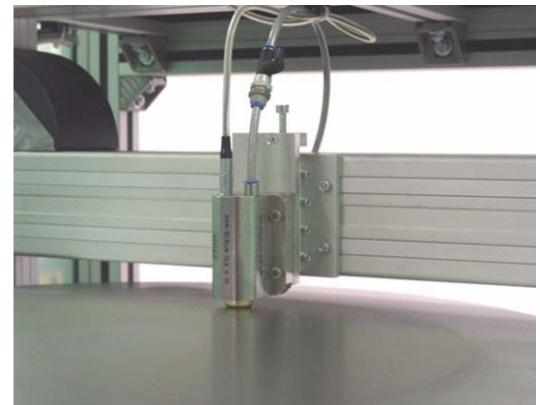


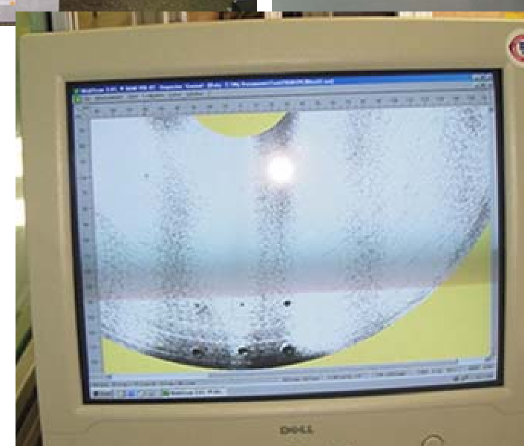
Cavity Treatment Procedures (1)

Limitation	Action
Suppression/Elimination of Multipacting	• Modification of cavity shape to spherical or elliptical cross section • Very clean surfaces to lower SEE
Suppression/Elimination of defects	• Improved inspection (Eddy current scanning of defects) • Improved EBW • Improved chemical treatment (Internal chemistry in clean room, filtered acids, EP) • Improved rinsing: HPR, ozonized water • Deeper material removal, tumbling • Class 10 clean room assembly

Procedures

Eddy Current Scanning system for SNS high purity niobium scanning

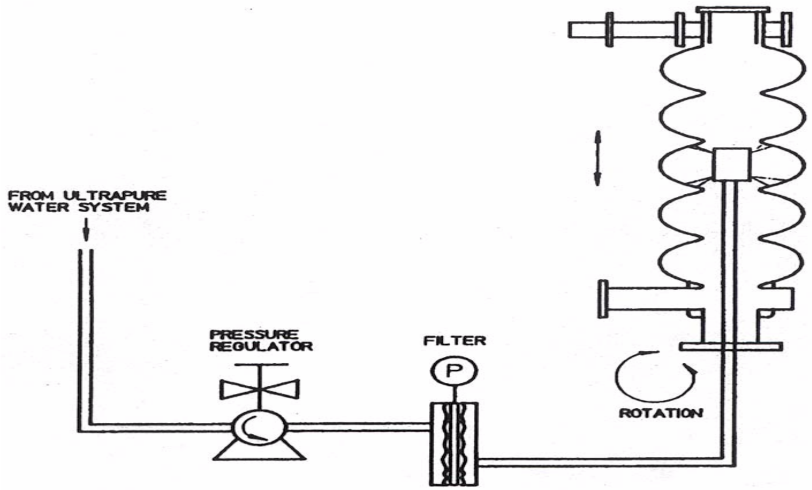




Cavity Treatment Procedures (2)

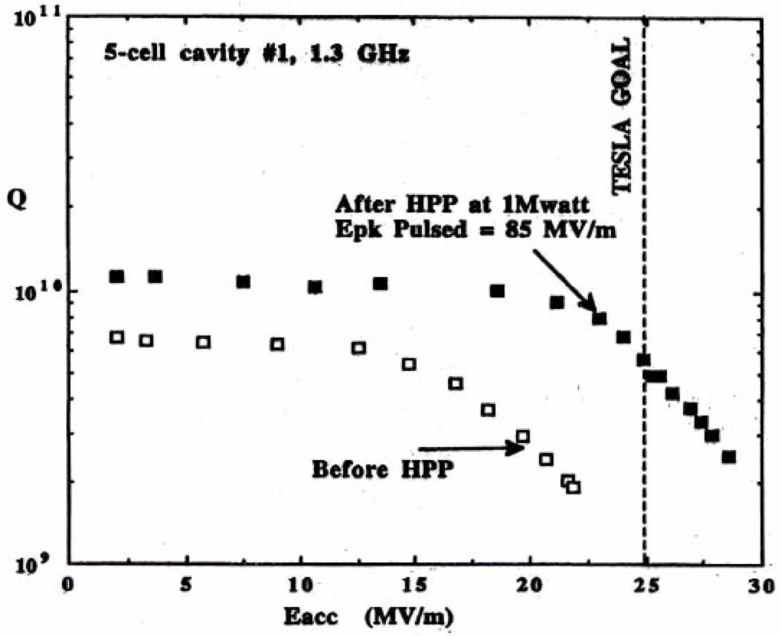
Limitation	Action
Stabilization of Defects	• Purer material : RRR > 250 • Solid State gettering
Field Emission	• High pressure, ultrapure water rinsing • Ozonized water rinsing • Electropolishing • Vacuum baking • High peak Power Processing • Class 10 clean room assembly • Improved contamination control

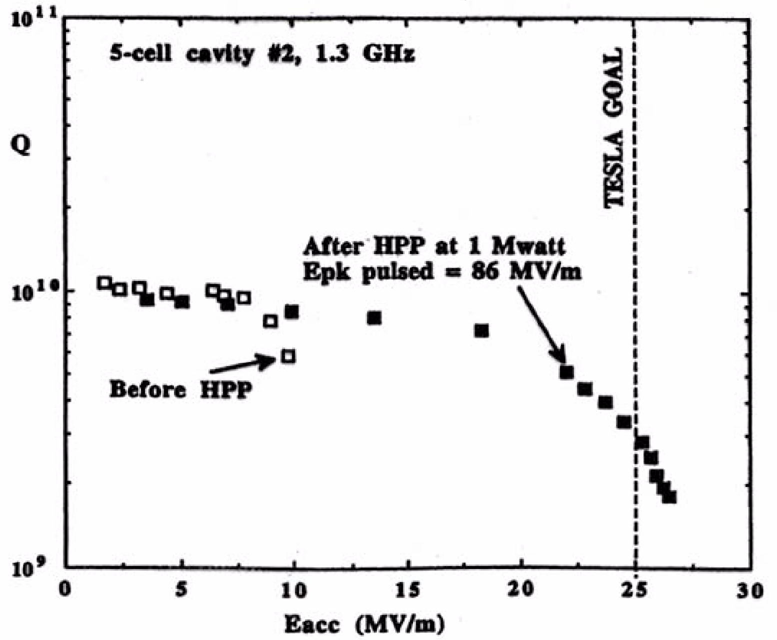
High Pressure Rinsing



High Peak Power Processing

Results obtained at Cornell University





Electropolishing

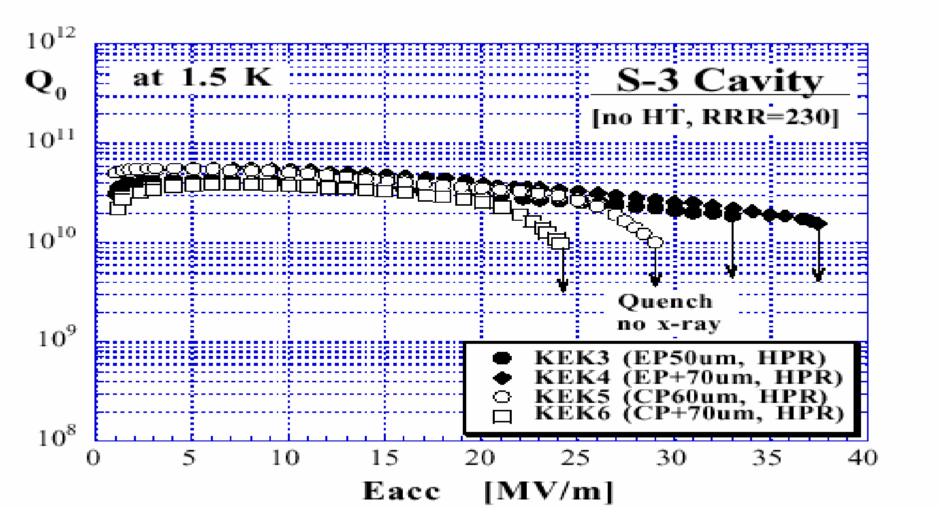
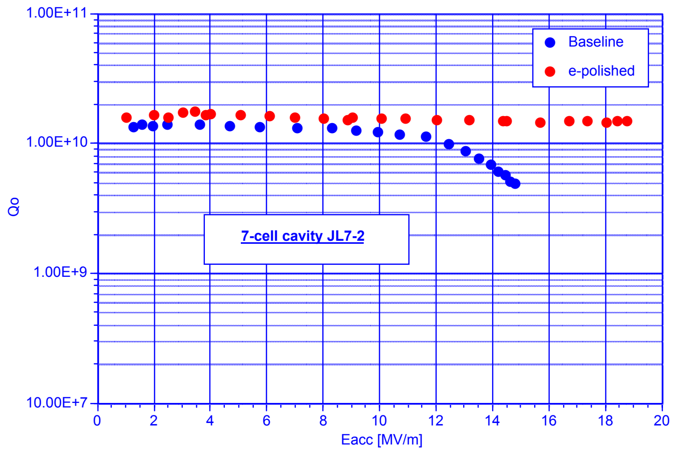
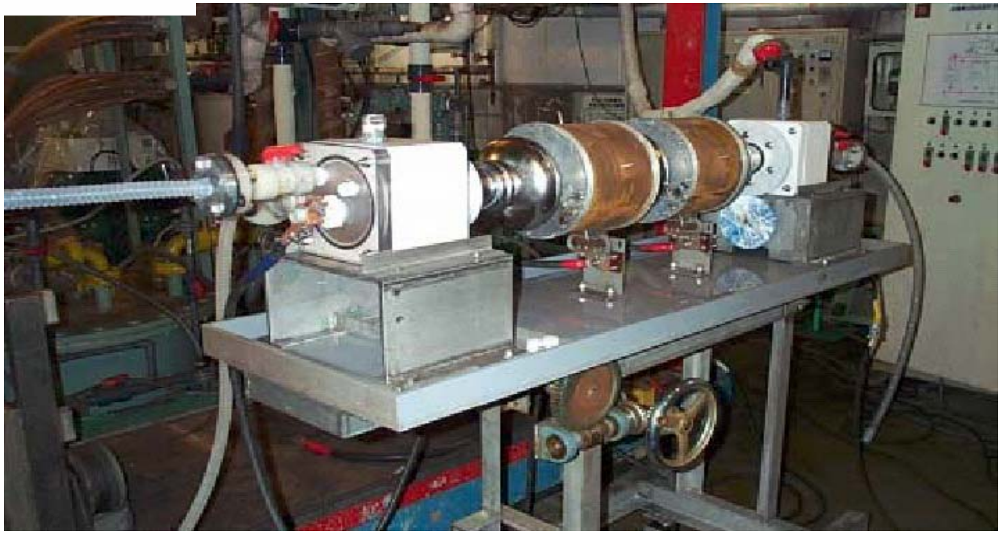


Figure 4: Cavity degradation due to CP after EP





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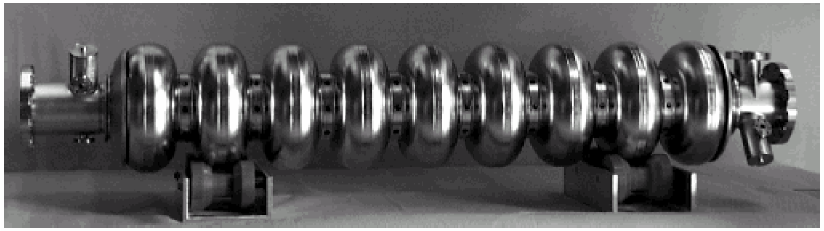
Experimental Results

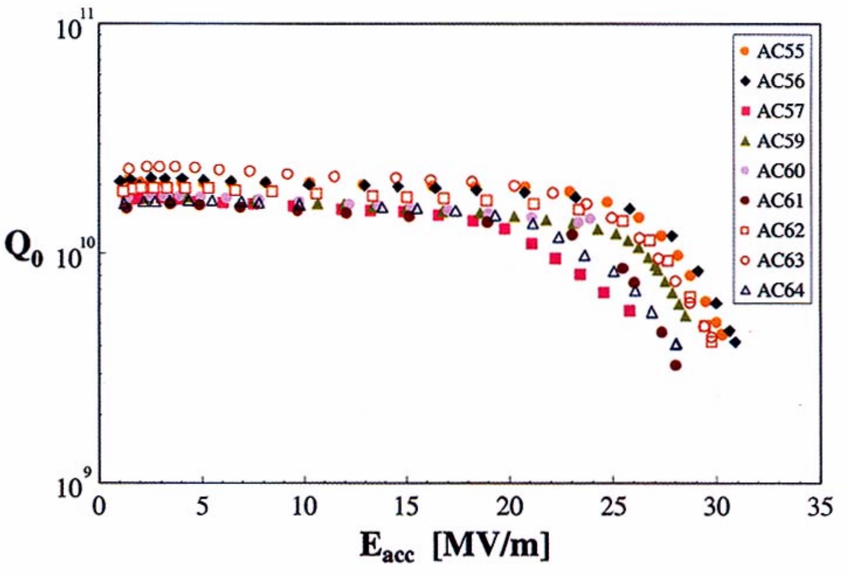
Table 2: Summary of multi-cell cavity results at various Laboratories.

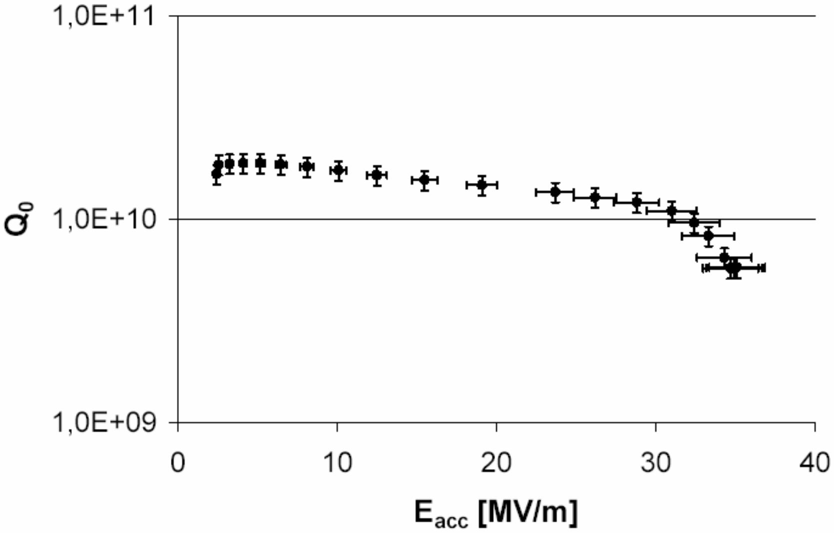
Project/Lab	Structure	Results	Reference
TTF/TESLA/DESY	9-cell, 1300 MHz $\beta = 1$	$20 < E_{acc}$ [MV/m] < 35	[13,18]
Upgrade/Jlab	7-cell, 1497 MHz $\beta = 1$	$10 < E_{acc}$ [MV/m] <19	[19]
SNS/JLab	6-cell, 805 MHz, $\beta = 0.61$ and 0.81	$10 < E_{acc}$ [MV/m] <19	[20]
JAERI/KEK Joint JAERI	5-cell, 600 MHz $\beta = 0.604$	$9 < E_{acc}$ [MV/m] <11.6	[21]
APT/LANL	5-cell, 700 MHz $\beta = 0.64$	E_{acc} [MV/m] ~ 12	[22]
RIA/MSU, Jlab	6-cell, 805 MHz, $\beta = 0.47$	Under fabrication	[23]
JAERI/KEK Joint KEK	9-cell, 972 MHz $\beta = 0.6$	Under fabrication	[17]
TRASCO/INFN	5-cell, 704 MHz $\beta = 0.85$	E_{acc} [MV/m] ~ 10 Sputtered Niobium	[16]
ASH/Saclay, Orsay	5-cell, 700 MHz $\beta = 0.65$	Under fabrication	[15]

Experimental Results

DESY 9-cell cavities

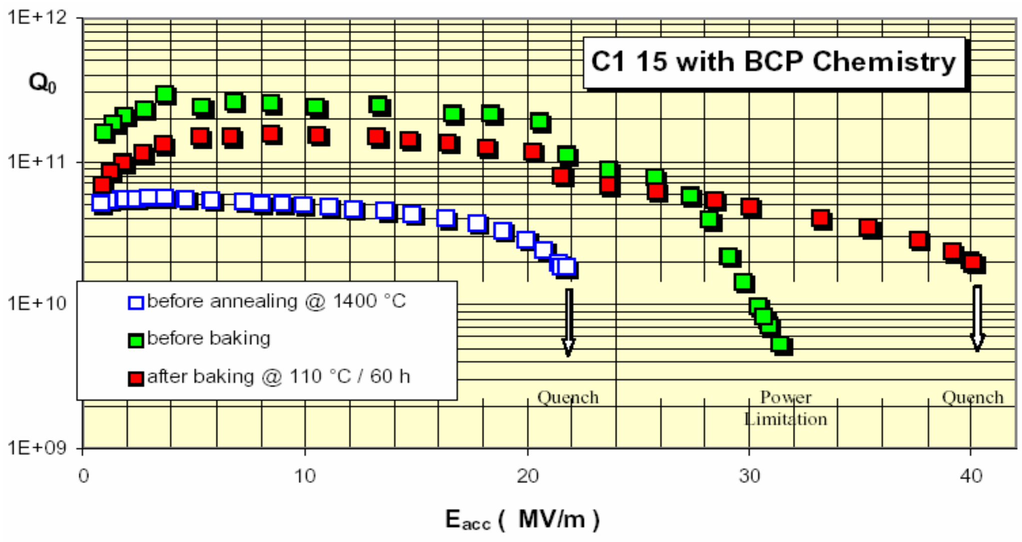




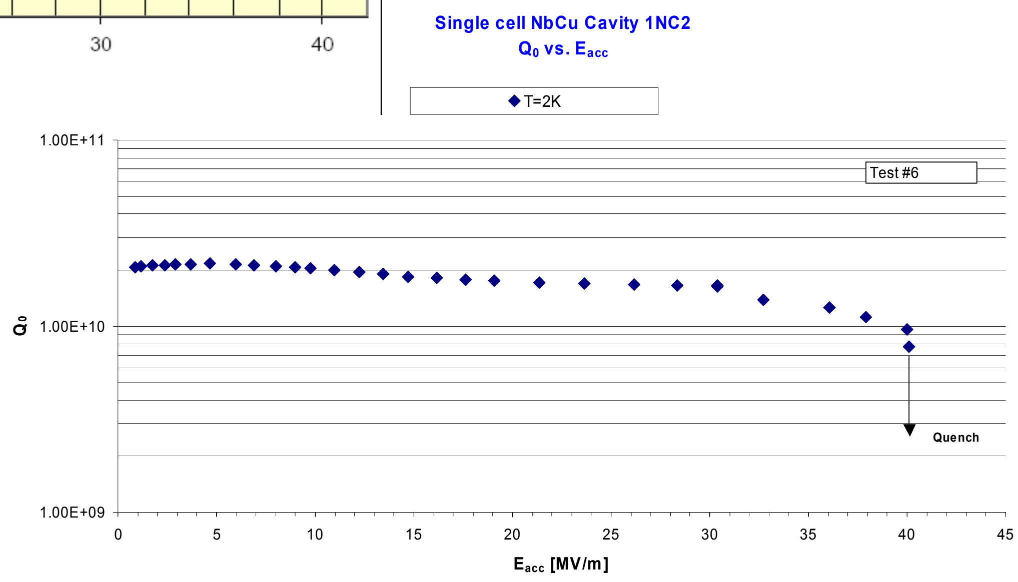


Experimental Results

Recent Result from CEA Saclay on Single Cell Cavity (B. Visentin)



Nb/Cu Cavity DESY/Jlab



Experimental Results

JAERI/KEK Joint Project

Fig. 1 600MHz 5-cell cavity (β=0.604)

Table 1 Design parameters for cavity

Resonant Frequency, [MHz]	600
E_{peak}/E_{acc}	3.45
H_{peak}/E_{acc}, [Oe/(MV/m)]	72.28
R/Q, [Ω]	154
Geometrical factor, [Ω]	166

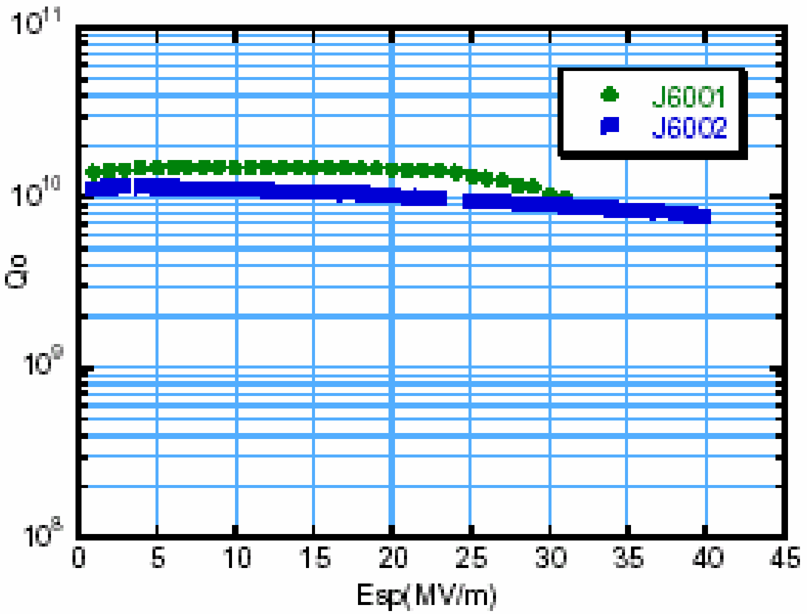
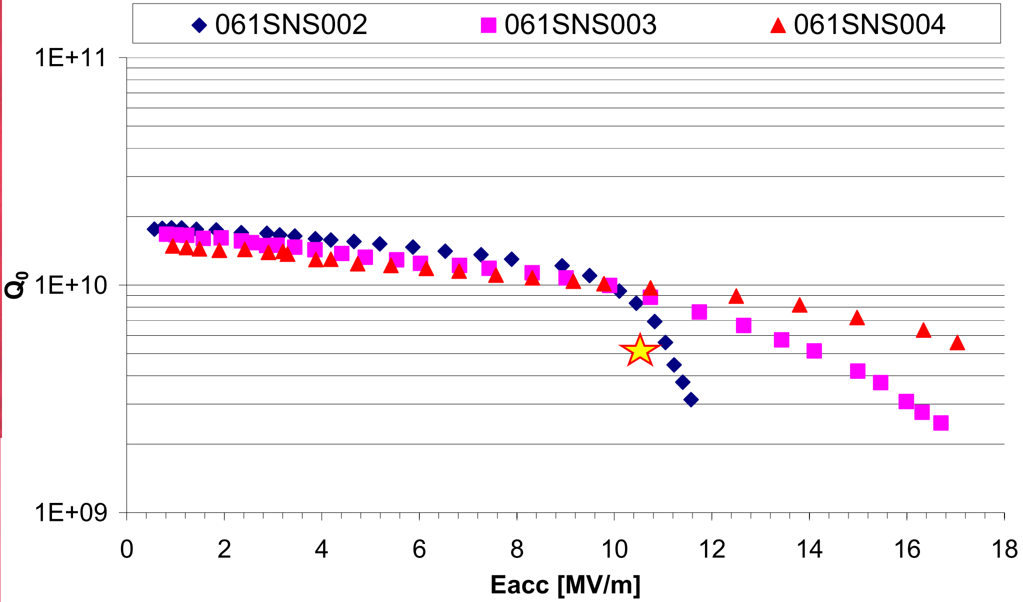


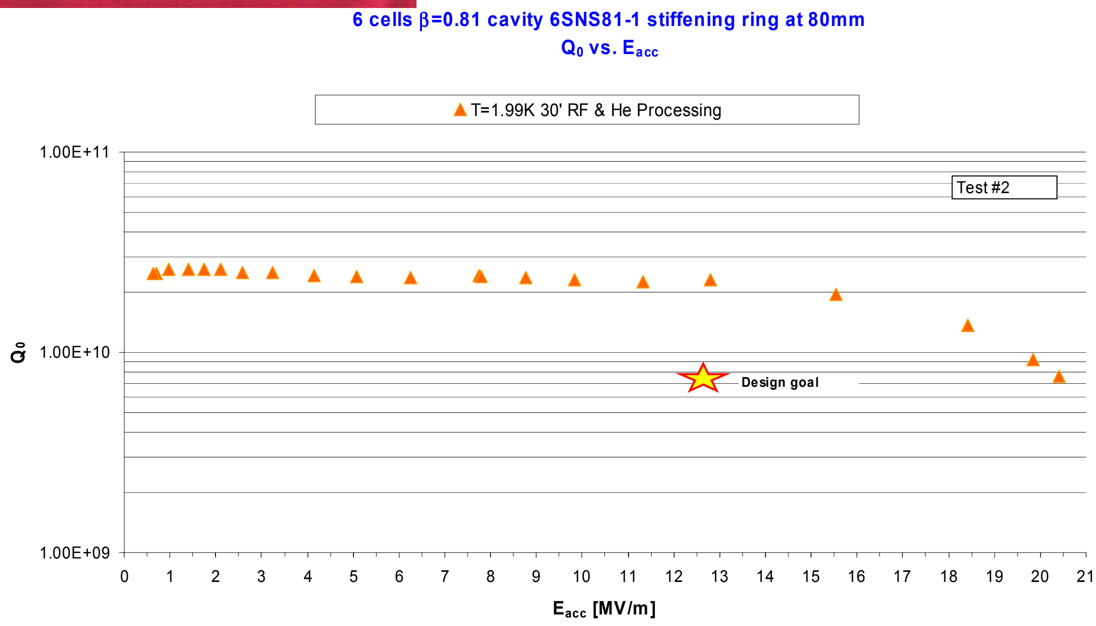
Fig. 5 Results of the vertical test

Experimental Results

SNS β=0.61Cavities

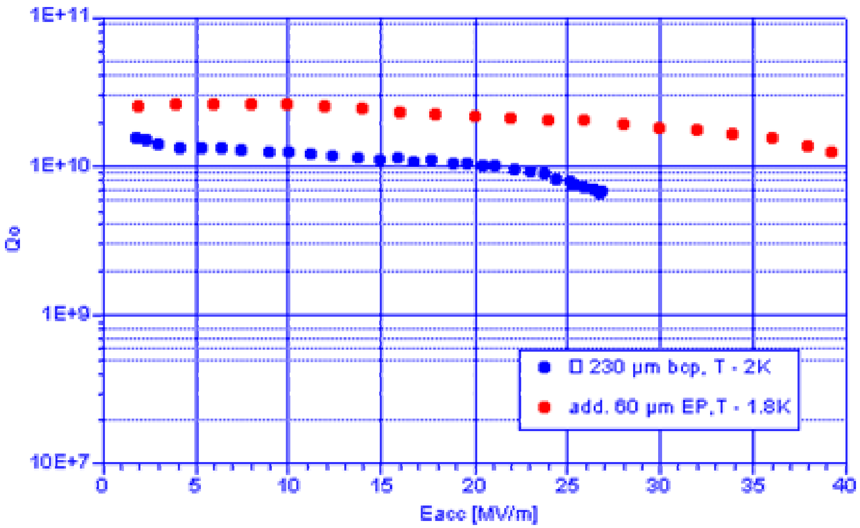


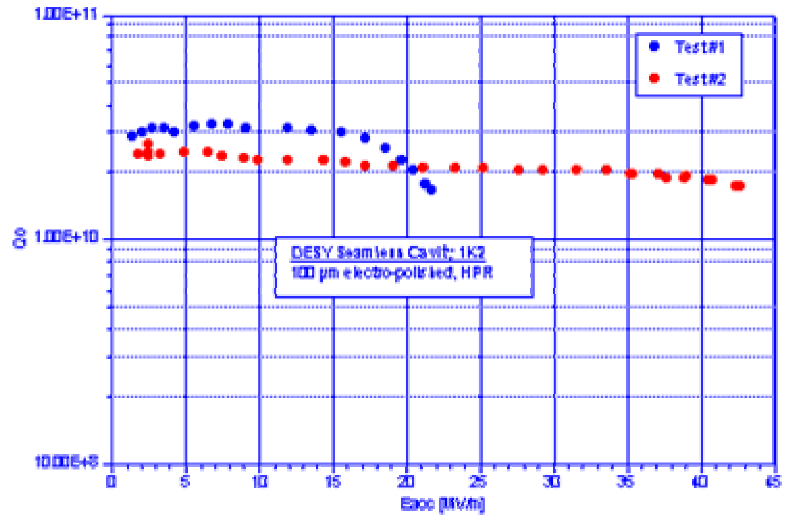
Experimental Results, SNS β = 0.81



Experimental Results

Electropolished cavities (done at KEK)





Summary (1)

- SRF Technology is considered for many future applications as a result of significant achievements in the past years
- In many cases now the fundamental limits for Niobium as the material of choice for sc cavities have been reached in single cell cavities
- One recent test result at DESY with a 9-cell cavity came close to these results : E_{acc} = 35 MV/m

EPAC 2002, June 3-7,Paris

Jefferson Lab

Summary (2)

- The main limitation is however field emission caused by "artificial" contamination
- Therefore improvement of cleaning procedures and prevention of re-contamination during assembly of larger system are the "high priority" tasks