Development of Superconducting Nb for Accelerator Structures at Stanford University: 1966 - 1979

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Why use Nb

- Benefits
  - High transition temperature: T_c = 9.26 K
  - High critical magnetic field: H_{c1} = 1735 Oe
  - Refractory metal: melting temperature = 2477 ^{o}C
    - Good electron-field-emission properties
    - Resistant to damage from heating and arcing
  - Stable surface oxide resistant to corrosion
  - Structurally suitable for fabricating accelerator structures
- Questions
  - Is surface impedance described by BCS theory
  - What is the limiting rf magnetic field
  - Methods to produce Nb accelerator structures
    - Initial tests with a CVD Nb film did not look promising
    - Solid Nb cavities (cost, fabrication & processing methods)

1967 - 1968
11.2 GHz TE_{011}-mode Nb cavities, (I. Weissman, J.P. Turneaure)

Cavity preparation

- Composed of 3 parts
  - Right circular cylindrical section
  - 2 end plates
- Reactor grade Nb
  - Arc melted (AM)
  - Electron beam melted (EBM)
  - Recrystallized fully wrought (RFW)
- Processing methods
  - Mechanical polishing
  - Chemical polishing
  - Electropolishing
  - UHV firing at 2000 – 2100 ^{o}C

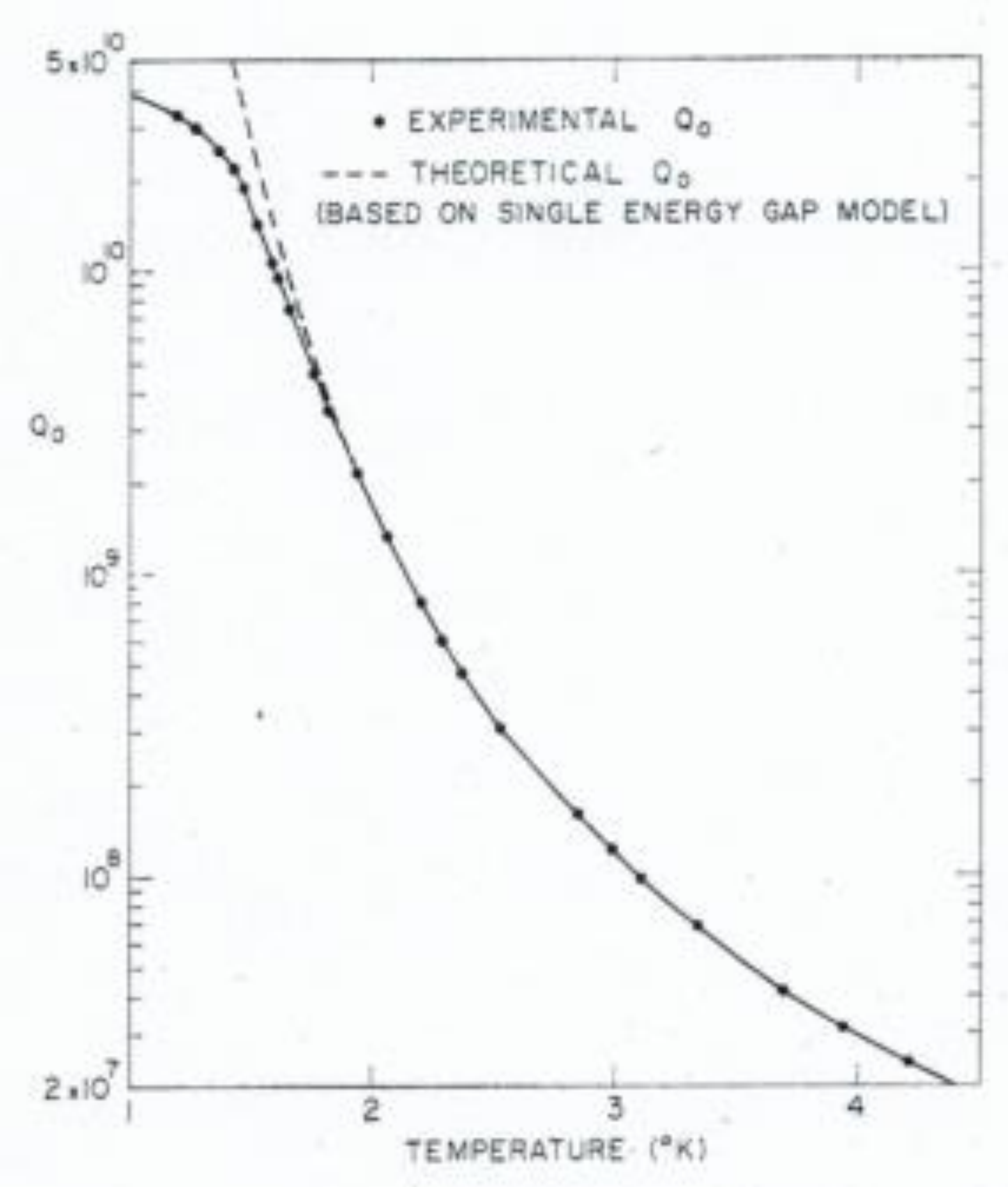
Summary results

- Mechanically polished surfaces gave poor results
- EB melted Nb parts with 6 crystals
  - Q_0 at 1.2 K: 1.3×10^{10} & 3.2×10^{10}
  - H_{max} = 259 & 436 Oe
- AM Nb parts with 6.2 mm crystal size
  - Q_0 at 1.2 K = 3.7×10^{9}
  - H_{max} = 398 Oe
- Results for UHV fired RFW Nb parts
  - Q_0 at 1.2 K = 2.8×10^{9}
  - H_{max} = 411 Oe

BCS theory at high frequency accurately describes Nb data

11.2 GHz TE_{011}-mode Nb cavity

- Q_0 measurements from 1.2 to 4.2 K
- $R_{exp} = \Gamma/Q_0 = 752/Q_0$ ohms
- $R_{exp} = A\ R_{BCS}(T,\omega,\Delta(T),v_f,n,l) + R_{res}$ with A, $\Delta(0)$, R_{res} as free parameters
  - A = 1.01
  - $2\ \Delta(0)/(k_B\ T_c) = 3.72 \pm 0.01$
  - $R_{res} = 20\ n\Omega$ ($Q_{res} = 3.8\times10^{10}$)



1969
TM_{010}-mode EB-welded Nb cavities at 8.6 GHz
(J.P. Turneaure, N.T. Viet)

Cavity preparation

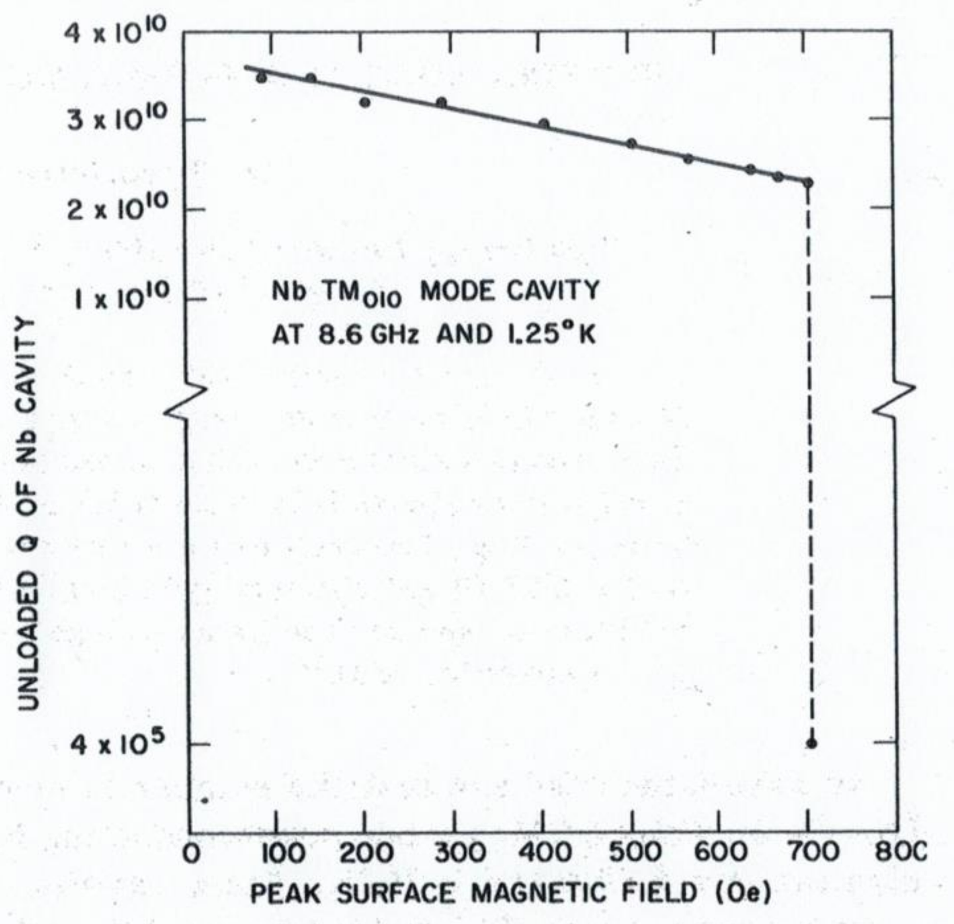
- Halves machined from annealed RFW reactor grade Nb rod
- 100% penetration EB weld at midplane of cavity
- UHV firing from 1750 – 2100 ℃
- Chemical polishing
- Assembled in glove box with dry nitrogen to a copper tubulation and to coaxial ceramic window
- Rough pumped with a sorption pump
- Pumped with an ion pump & baked at 100 ^{o}C for 10 hours
- Cooled to room temperature with a final pressure of less than 10^{-9} Torr
- Tubulation pinched off to form a permanent vacuum

TM_{010}-mode Nb cavity with 26.7 mm ID

Results for TM_{010}-mode EB welded Nb Cavities

- Q_0's as high as 10^{11} (3 nΩ)
- Peak surface mag. field of 1080 Oe
  Peak axial electric field of 47 MV/m
  with $Q_0 = 8\times10^9$
- 1080 Oe is 62% of H_{C1}
  - Field limited by thermal instability
- No electron multipacting observed
  - Shortest cavity length of 0.215 λ
  - Lowest order 2-sided multipacting possible is 4th order
- X-radiation observed for one cavity test
  - The cavity was exposed to the ambient atmosphere for several days prior to assembly
  - Cleanliness of Nb surface is important

Example of Q_0 as a function of Magnetic Field



1970 - 1979

Prototype TM_{010} Nb cavities & multicell Nb structures at L-band & S-band

(P. Kneisel, Y. Kojima, C. Lyneis, M. McAshan, H. Schwarz, J. Sayag, H.A. Schwettman, J.P. Turneaure, N.T. Viet)

Manufacturing methods

- Round RFW reactor grade Nb sheet 5 mm thick sheet
- Hydroform into a cup & stress relieve
- Machine half cells
- EB welding of half-cells to form a cavity or multicell structure
- UHV fire @ 1800 - 2000 ^{o}C
- Chemically polish
- Electropolish
- Anodize
- Assemble in glove box or equivalent

In-house facilities

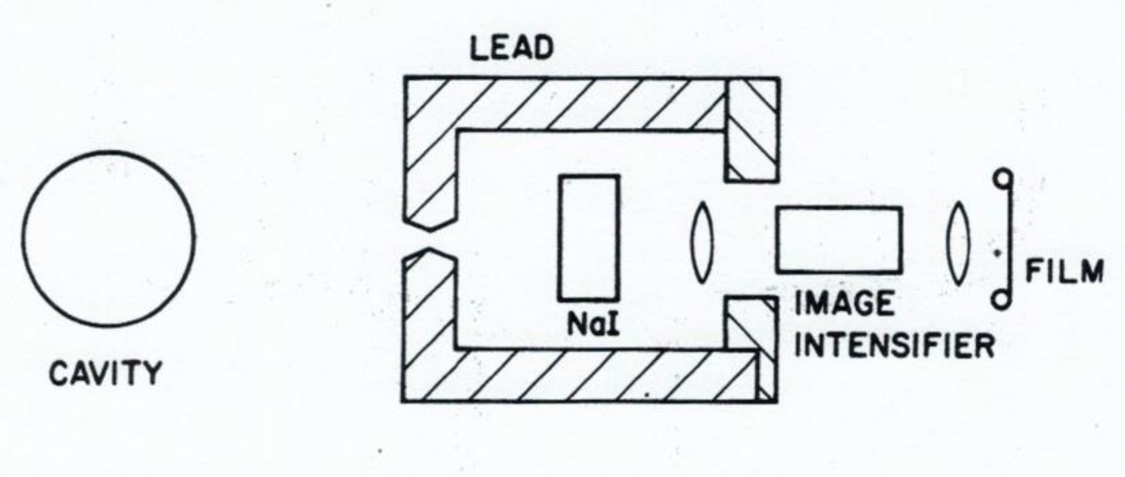
- Machine lathes with tracer attachments and vacuum chucks
- HV electron-beam welder
- Unique UHV furnace
    - Temperature up to 2500 ^{o}C
    - Hot zone 30 cm diameter by 90 cm long
- Chemical processing room with remote handling of parts
- Temperature controlled room for measuring frequency & field profile
- Glove box for assembling cavities & structures

Summary results of TM_{010}-mode Nb cavities and multicell structures at L-band & S-band

- Q_0's from 2×10^9 to 4×10^{10}
- Peak axial electric fields (peak surface magnetic fields) up to
  - E_a = 15 MV/m (H_p = 350 Oe) at 1.3 GHz
  - E_a = 24 MV/m (H_p = 650 Oe) at 2.8 GHz
  - Peak fields increased with frequency (E_a = 47 MV/m (H_p = 1080 Oe) at 8.6 GHz)
- X-radiation due to electron field emission occurred at high electric field
- Electron multipacting was observed in all cavities & structures
  - Higher order multipacting field levels could be passed through
  - Lower order multipacting often limited the field that could be reached
- Cavities with a sealed vacuum after UHV bakeout at 100 ^{o}C performed better
  - No degradation after hours of operation with strong electron field emission
- Regenerative excitation of other high-Q modes occurred in the presence of strong electron multipacting and electron-field-emission loading
  - Eliminated by selectively loading appropriate high-Q modes

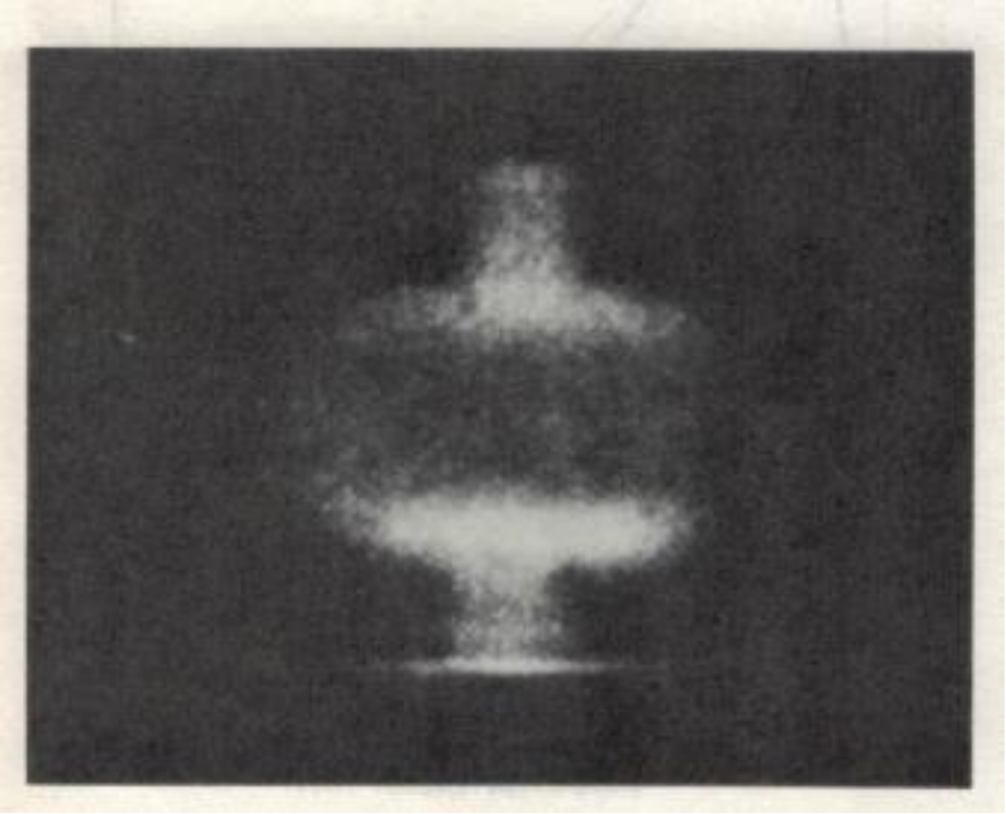
Electron field emission study of TM_{010}-mode cavity at 1.2 GHz

(I. Ben-Zvi, J. Crawford, J.P. Turneaure)



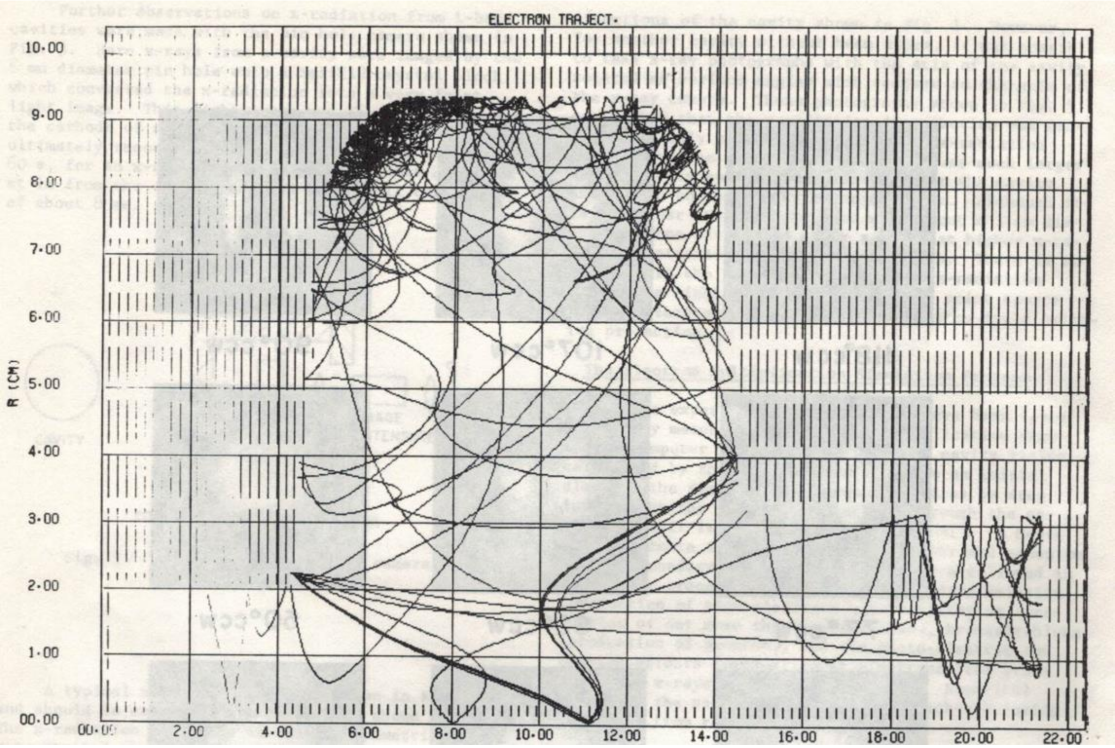
- X-ray photo of cavity with pin hole camera
- X-ray image is axisymmetric
  - Verified by other views

X-ray photo of TM_{010}-mode cavity at 1.2 GHz with a 17.7 mm ID



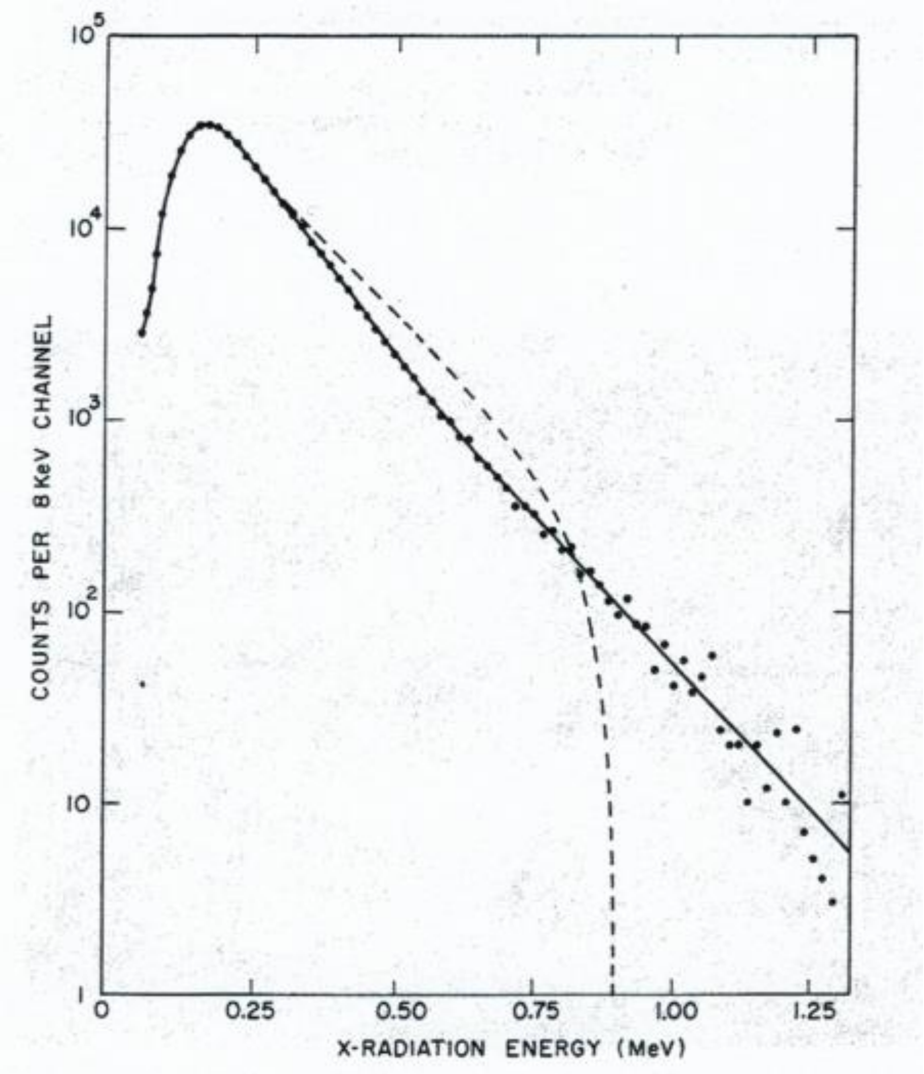
Monte-Carlo simulation of the multiplication of EFE electrons

- Simulation of 88 initial EFE electrons
  - Followed secondary electrons and one or zero backscattered electrons
  - Stopped after 70 electrons produced
- Max simulated impact energy was 0.89 MeV
  - Limited by # of initial electrons
- Produced a non-resonant cloud of low energy electrons at outer radius
- Electrode at outer radius
  - < 10 nA during EFE loading
  - -300 μA during electron multipacting



Experimental & simulated X-ray spectra agree

- X-rays pass through 3 mm Nb, 5 mm Al, 0.5 mm Fe, & 100 mm liquid He
- Spectrum taken with a NaI crystal
- Counting rate of 800 cnts/s with pulses decaying in 1 μs
  - Chance coincidences were not a problem
- Maximum energy of 1.3 MeV
  - 2.4 times max energy for a single pass
- Simulated spectrum is dashed curve
  - Max energy of 0.89 MeV is the result of limited number of initial electrons
- **Simulation program served as the precursor for a program to simulate single-point electron multipacting**

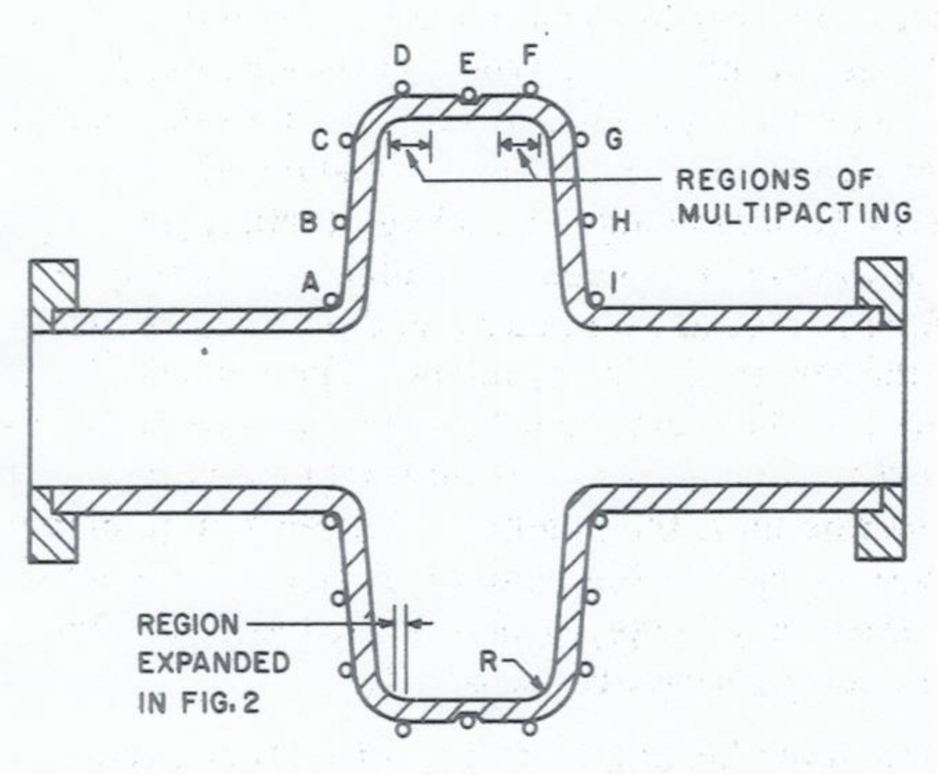


Location of electron multipacting in TM_{010}-mode cavity

(C.M. Lyneis, H.A. Schwettman, J.P. Turneaure)

- Features of 2.8 GHz TM_{010}-mode cavity
  - R = 4.7 mm
  - Anodized to enhance secondary electron emission
  - Instrumented with thermometers to locate position of heat dissipation
- During multipacting temperature increase was observed in temperature sensors D & E or E & F
  - Location of temperature increase consistent with multipacting simulation

Instrumentation of cavity with thermometers spaced along the r-z surface and around the axis



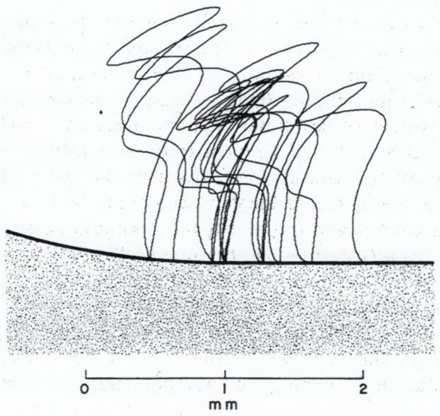
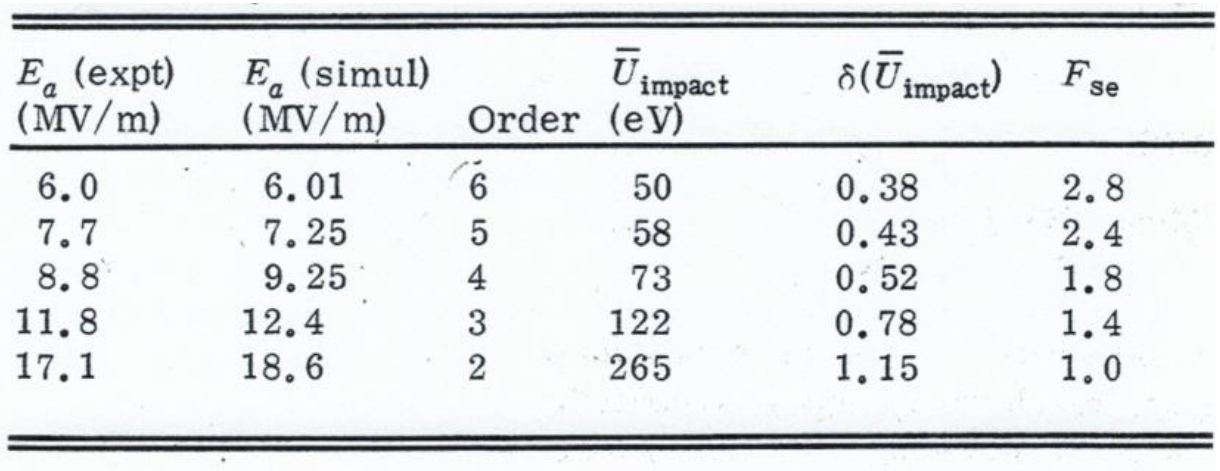


Fig. 2. Example of electron trajectories for 3rd order single-point electron multipacting calculated with simulation program

Single-point electron-multipacting experiment & simulation agree

Electron-multipacting experimental & simulated electric field levels for TM_{010}-mode cavity



E_a (expt) (MV/m)	E_a (simul) (MV/m)	Order	$\overline{U}_{\mathrm{impact}}$ (eV)	$\delta(\overline{U}_{\mathrm{impact}})$	F_{se}
6.0	6.01	6	50	0.38	2.8
7.7	7.25	5	58	0.43	2.4
8.8	9.25	4	73	0.52	1.8
11.8	12.4	3	122	0.78	1.4
17.1	18.6	2	265	1.15	1.0

E_a (expt): experimental electric field level
E_a (simul): simulated electric field level
Order: order of single-point electron multipacting
$\underline{U}_{\mathrm{impact}}$: Average energy of electron impact
$\delta(\underline{U})$: secondary emission coefficient a Uimpact
F_{se}: Secondary emission enhancement factor

No electron multipacting in 2.8 GHz TM_{010}-mode cavity with sharp corner

- Simulated multipacting of a sharp-cornered (R = 0) TM_{010}-mode cavity
  - No electron multipacting with increasing fields through 3rd order multipacting

- Produced S-band TM_{010}-mode Nb cavity with corner radius of 0.38 mm
  - Anodized Nb to enhance secondary electron emission
  - No electron multipacting with increasing fields through 3rd order multipacting

What was learned from 1966 to 1979?

- The surface impedance of superconducting Nb is accurately described by the BCS theory as extended to high frequency by Mattis and Bardeen
- Q_0's from 2×10^9 to 4×10^{10} are relatively easy to attain
- A field of 1080 Oe was demonstrated, which is 62% of H_{C1}
  - Limited by thermal runaway, not superconductivity
- An appropriate cavity geometry can mitigate electron multipacting
- UHV & Cleanliness of the superconducting surface are very important
- Accelerator structures can be successfully manufactured and processed with RFW reactor grade Nb
  - By the beginning of 1974, we produced four 6 m 1.3 GHz Nb accelerator structures for the Stanford linac