Perspectives on Superconducting RF

A workshop in celebration of the career of Peter Kneisel

Thomas Jefferson National Accelerator Facility

May 19, 2014

Pioneers of SRF

How SRF made it out of the laboratory and into the first accelerators

H. A. Schwettman

Stanford University

Early History of SRF

Based on a two-fluid model of superconductivity H. London in 1934 pointed out that resistive losses should be observable in superconductors at very high frequencies.

In 1940 he immersed an ellipsoidal tin sample in a 1.5 GHz RF field and made calorimetric measurements of the power dissipated in the sample, qualitatively confirming his prediction.

SRF Following WW II

Pippard in 1947 at Cambridge made measurements using a hairpin resonator at 1.2 GHz.

Maxwell, Marcus and Slater in 1948 at MIT experimented with a resonant cavity at 24 GHz.

Fairbank in 1949 at Yale made measurements of a resonant cavity at 9.4 GHz.

SRF in the 1950s

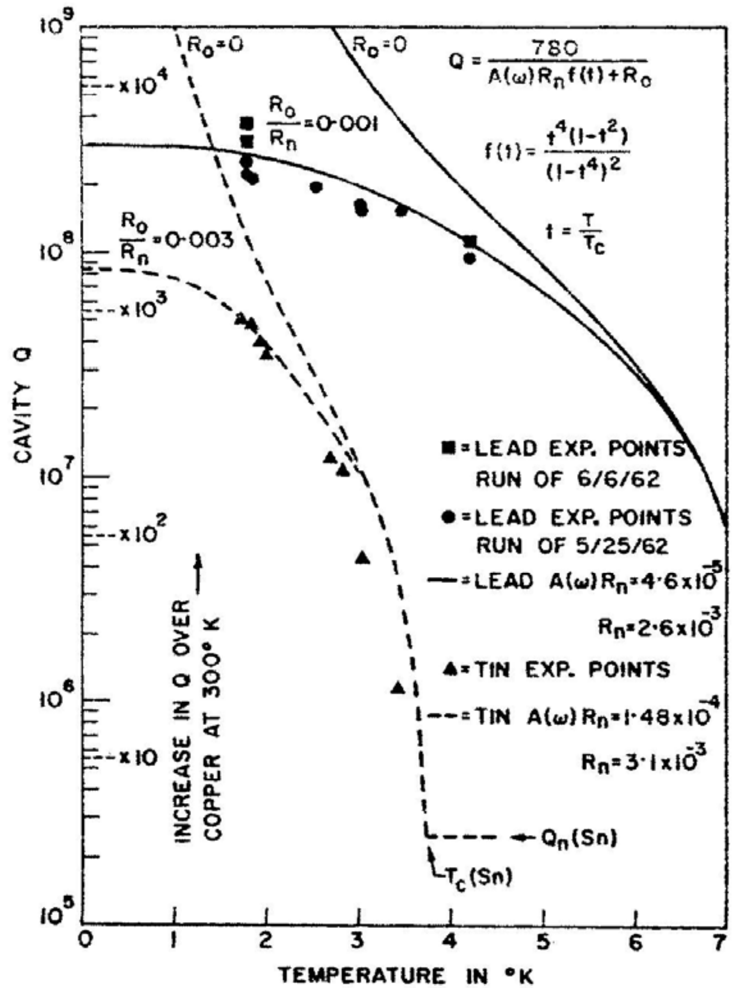
As liquid helium became more available, the number of groups interested in SRF increased. A review article by Maxwell cited 50 separate SRF articles. However, THE HIGHEST Q REPORTED IN THE LITERATURE OF THE 1950s WAS JUST $5x10^6$! ! !

The Landmark Stanford SRF Experiment

W. M. Fairbank, J. M. Pierce and P.B. Wilson, in Proceedings of the Eighth International Conference on Low Temperature Physics, London, 1962, p. 324.

Addressed the central physics issue, the losses associated with RF currents flowing in the superconducting surface. Achieved by selecting TE_{011} mode (zero electric field on walls and zero current at cavity joints with end plates).

The Landmark Stanford SRF Experiment



Cavity was fabricated from copper, electroplated with lead, and suspended in vacuum.

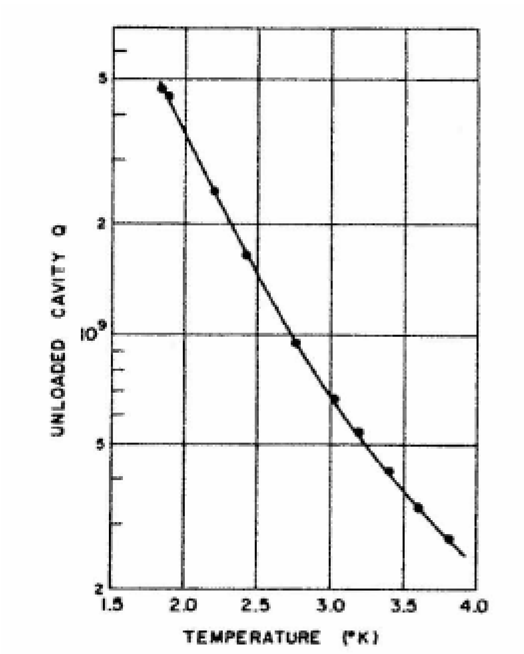
A Second Landmark SRF Experiment

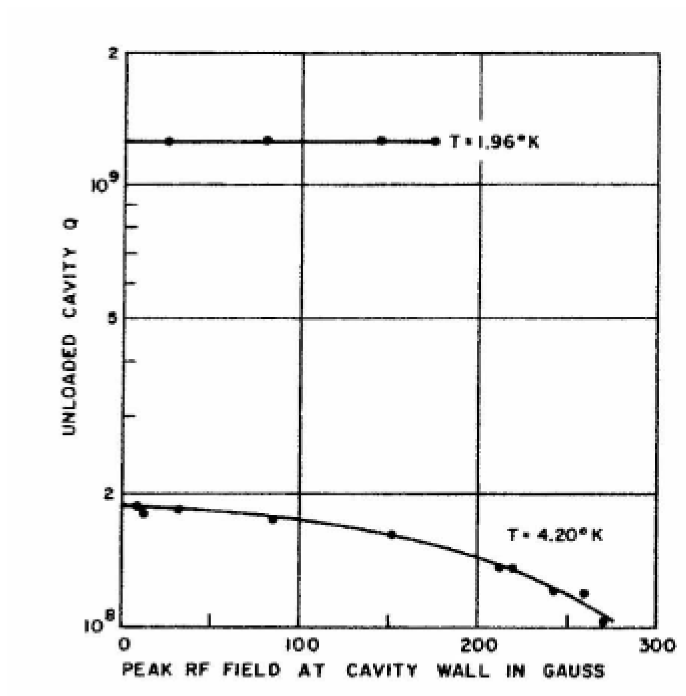
Addressed Central Technical Issues:

- Immerse cavity in liquid helium ... Develop suitable "gasket" to seal cavity.
- Provide stable RF source.
- Improve electroplating techniques.

H. A. Schwettman, P. B. Wilson, J. M. Pierce and W. M. Fairbank in *International Advances in Cryogenic Engineering,* edited by K. D. Timmerhaus (Plenum Press, New York, 1965), **10**, p. 88.

A Second Landmark SRF Experiment (continued)





Low power Q was 5x10^9 at 1.85 K and still rising.
Maintained Q above 10^9 at fields approaching 200 Gauss this corresponds to an accelerating gradient of approximately 5 MeV/m).

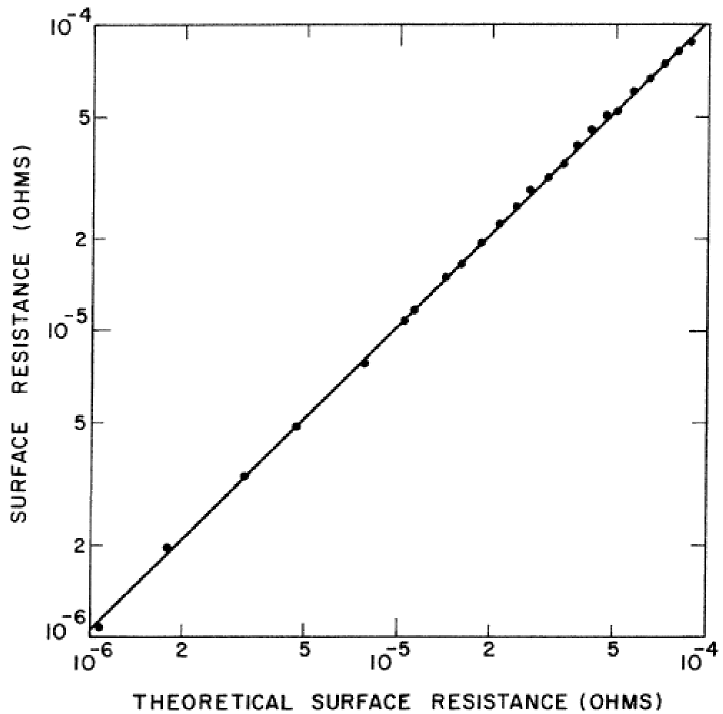
The Turneaure PhD Thesis

Two pronged study:

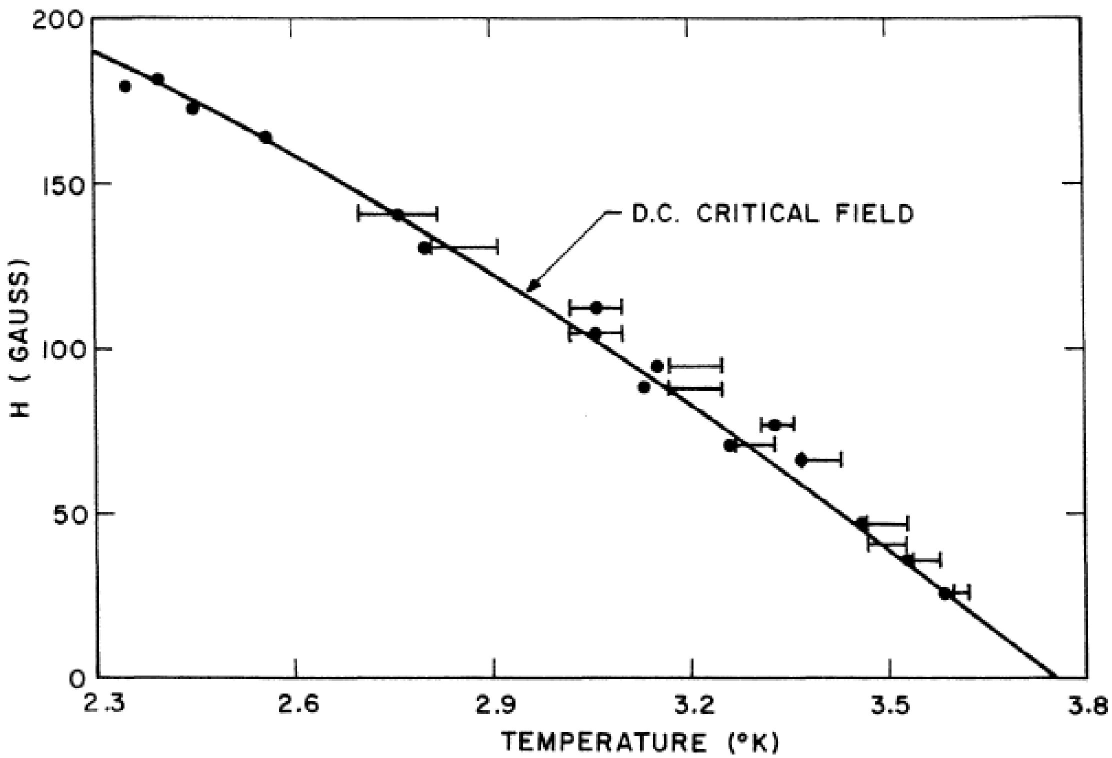
1. First opportunity to provide a detailed comparison of the T-dependent RF surface impedance of a superconductor with the full Mattis-Bardeen theory.
2. First demonstration that a superconductor will support an RF magnetic field at least up to H_C.

The Turneaure PhD Thesis (continued)

Surface Resistance of superconducting lead.



RF and DC critical field of superconducting tin



J.P. Turneaure, *Microwave Measurements on the Surface Impedance of Superconducting Tin and Lead*, PhD Thesis, Stanford University,1966.

The 5th International Conference on High Energy Accelerators
Frascatti, Italy 1965

In preparation for Conference we adopted a two pronged approach:

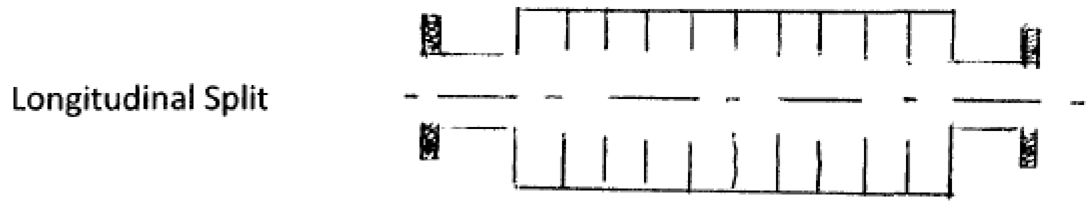
1. Study role of electric field in a single-cell TM_{010} cavity and a three-cell structure, both electroplated through the beam hole.

   Despite brazing problem, achieved $Q \sim 2 \times 10^8$ and energy gradient ~4 MeVlm.

H. A. Schwettman, P.B. Wilson and G.Y. Churilov, in *Proceedings of the 5th International Conference on High Energy Accelerators*, Frascati, Italy, (1965), p. 690.

The 5th International Conference on High Energy Accelerators Frascatti, Italy 1965 (continued)

2. Attempt to accelerate electrons in a multi-cell structure. We fabricated an 11-cell structure, split longitudinally (parallel to current flow) to enable electroplating in an open geometry.



We failed miserably to make the indium T-seal at the flange/longitudinal split connection!

In the last two weeks before the conference we fabricated a second three cell structure (with RF coupling off the beam line) and ACCELERATED AN ELECTRON BEAM TO 0.5 MeV IN A SUPERCONDUCTING STRUCTURE FOR THE FIRST TIME!!

Other Early Accelerator Laboratory Interest in SRF

Other Early…

- Banford and Stafford
  A.P. Banford and H. G. Stafford, *J. Nucl. Energy,* **3**, 287 (1961)
- CERN/Lausanne
  A. Susini, "Initial Experimental Results Concerning Superconductive Cavities at 300 Mc/s," CERN Internal Report 63-2, MCS Division (1963); J. Rüfenacht and L. Rinderer, Z. Angew. Math. U. Physics **15**, 192 (1964).

Somewhat Later…

- Karlsruhe
- Cornell

Scoping Out What Might Be Possible With SRF

	SLAC-1965	Possible?
Duty Factor	10^{-3}	1
Average Beam Current	30 μA	100 μA
Injector Phase Space Longitudinal Transverse	 100 keV/3° ?	 10 keV/1.5° 10 mm mr
Gradient	6.6 MeV/m	13.2 MeV/m*

* Hofstadter wanted a 2 GeV electron beam with only 500 feet available in the laboratory.

Electron Beam Duty Factor

Choice of linac frequency:

Switched from S-band to L-band.

Commitment to Superfluid Cryogenics:

FIRST Superfluid Helium Refrigerator.
(Arthur D. Little .... Sam Collins)

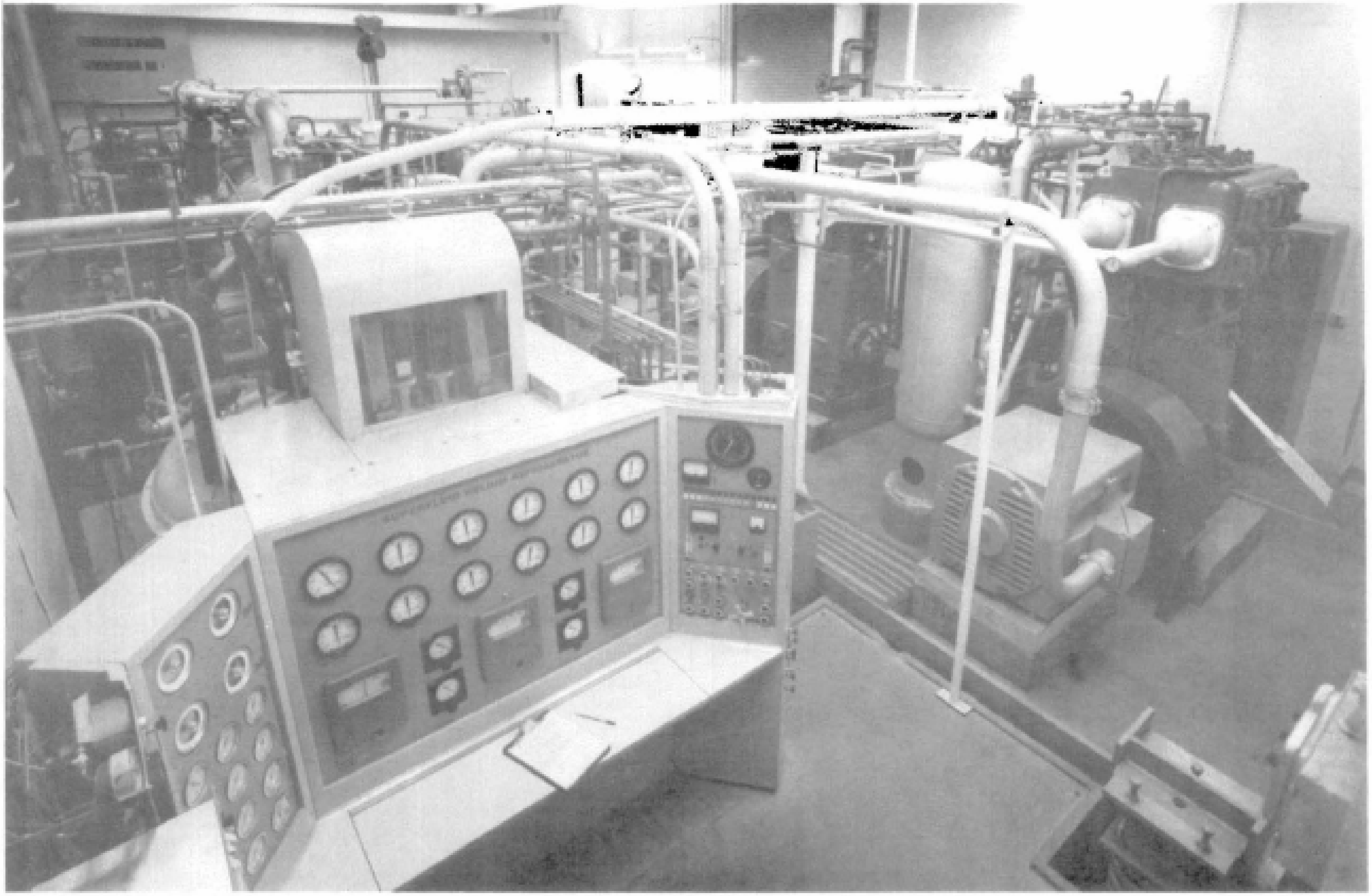
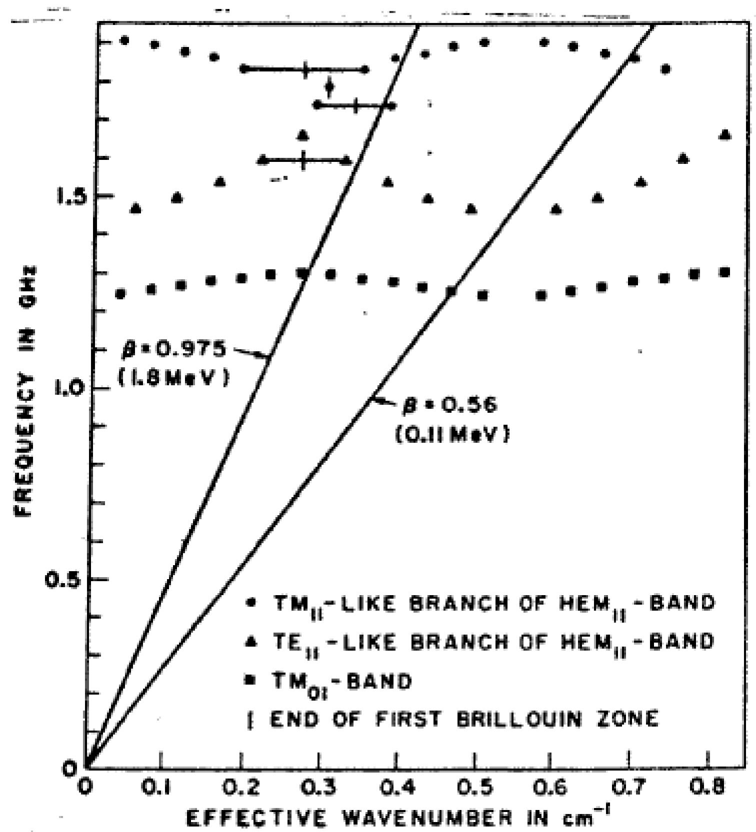


Fig. 2 Photograph of refrigerator.

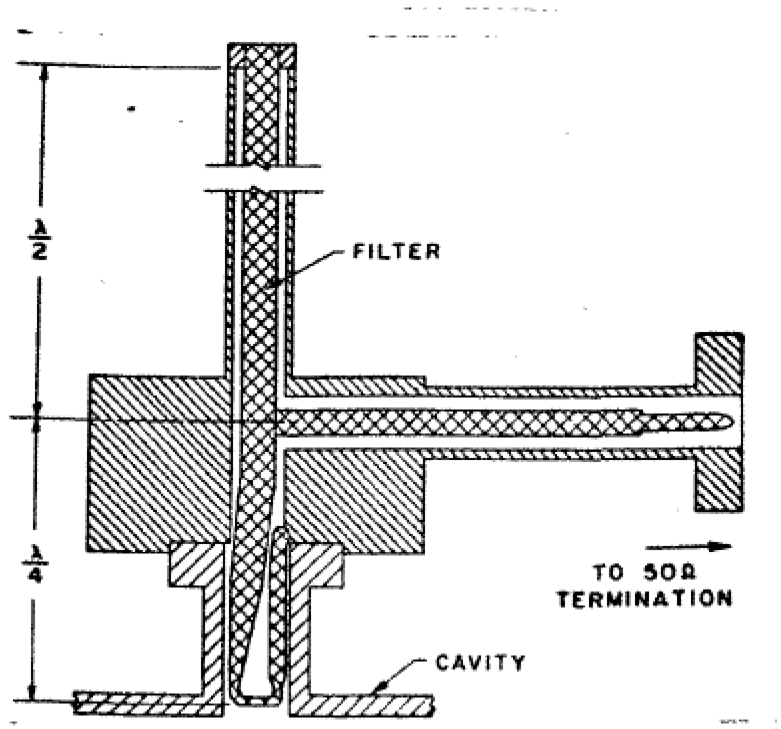
Average Electron Beam Current

Systematic measurements of starting currents for all modes in two lowest frequency dipole bands.



Average Electron Beam Current

FIRST external loading of HOMs



K. Mittag, H.A. Schwettman and H.D. Schwarz, Beam Breakup in a Superconducting Electron Accelerator, the 1972 Proton Linear Accelerator Conference, Los Alamos, New Mexico.

Injector Phase Space

(Achieve 10^{-4} $\Delta E/E$ at 2GeV and limit beam halo.)

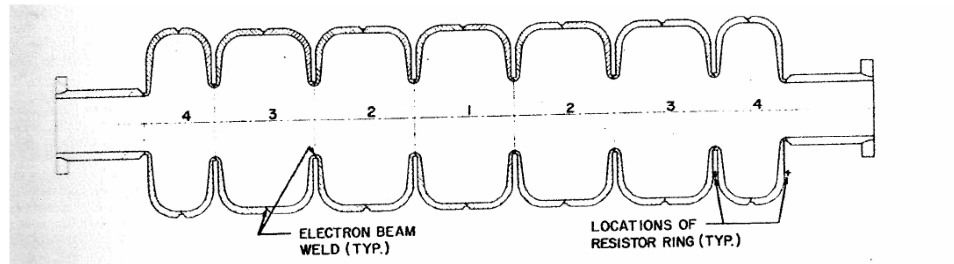
Approach to Problem:

FIRST feedback stabilization of accelerator field.

Careful injector design.

Gradient

- First Use of Short (7-cell) π-mode Structure

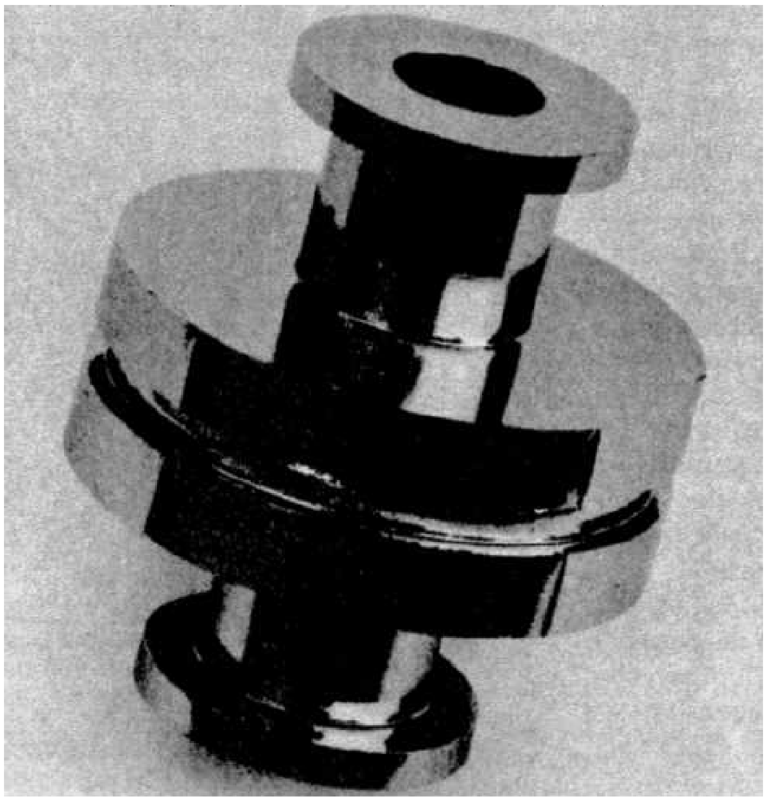


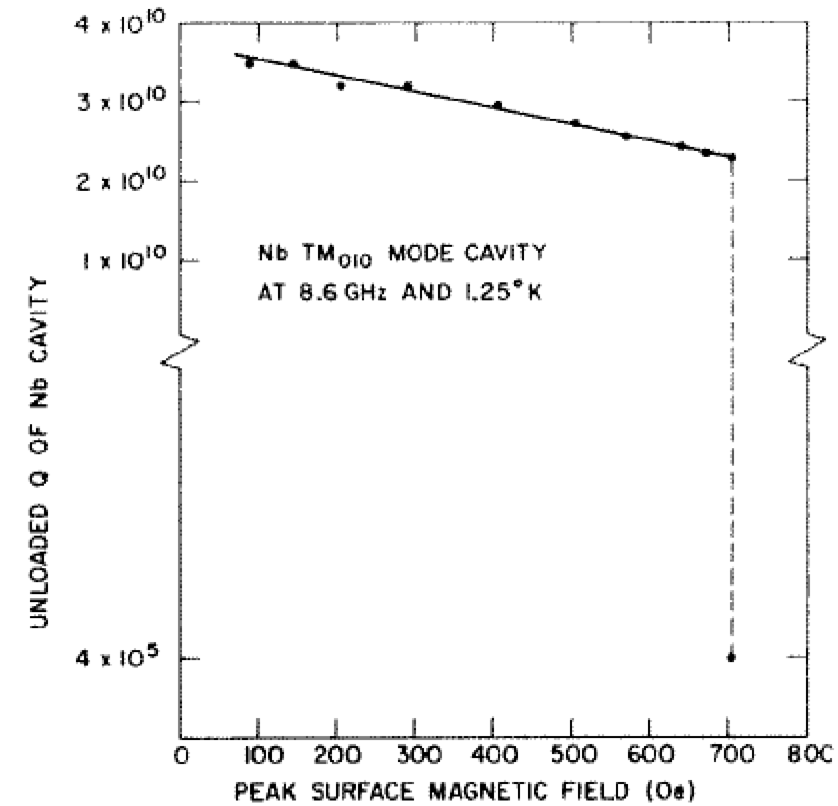
T. I. Smith, Standing wave modes in a Superconducting Linear Accelerator, HEPL TN437, (April 1966).

- Commitment to Superconducting Niobium
  Obtained high Q (~10^9) and high gradient (~10MeV/m) with large grain material, that was UHV fired and chemically polished.

J. P. Turneaure and I. Weissman, *J. Applied Phys.* **39**, 4417 (1968); I. Weissman and J. P. Turneaure, *Appl. Phys. Lett.* **13,** 390 (1968).

Landmark X-band TM010-Mode Cavity Experiment

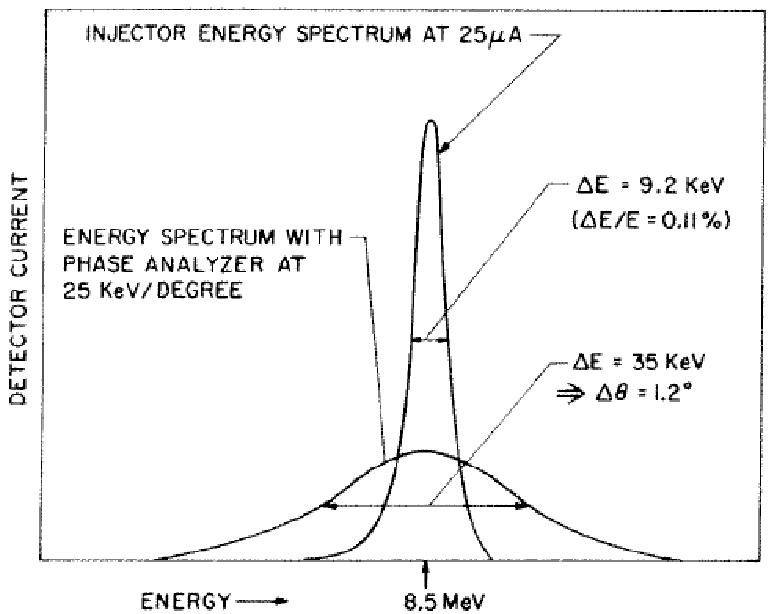




J. P. Turneaure and N. T. Viet, *Appl. Phys. Lett.* **16**, 333 (1970).

The Reality

- Demonstration of Injector As High Intensity, High-resolution Device



Energy Stability (30 minutes) ± 3 x 10^{-5}

Injector Emittance at 8.5 MeV 0.6π mm mr.

M. S. McAshan, K. Mittag, H. A. Schwettman, L. R. Suelzle, J. P. Turneaure, *Appl. Phys. Lett.* **22**, 605, (1973).

The Reality

- Performance of 6-m 1300 MHz Structure

Energy Gradient	3MeV/m
Q-value	$5x10^9$
Duty factor	100% at accessible gradient
Average Current	200 μA

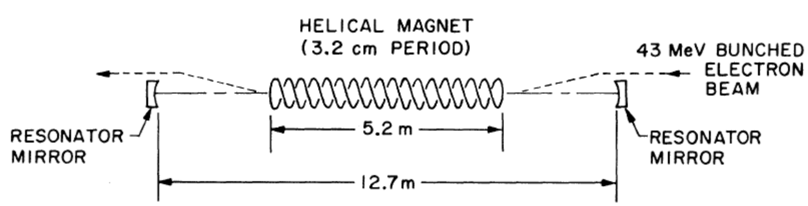
J. P. Turneaure, H. A. Schwettman, H. D. Schwarz, and M. S. McAshan, *Appl. Phys. Lett.* **25,** 247, (1974).

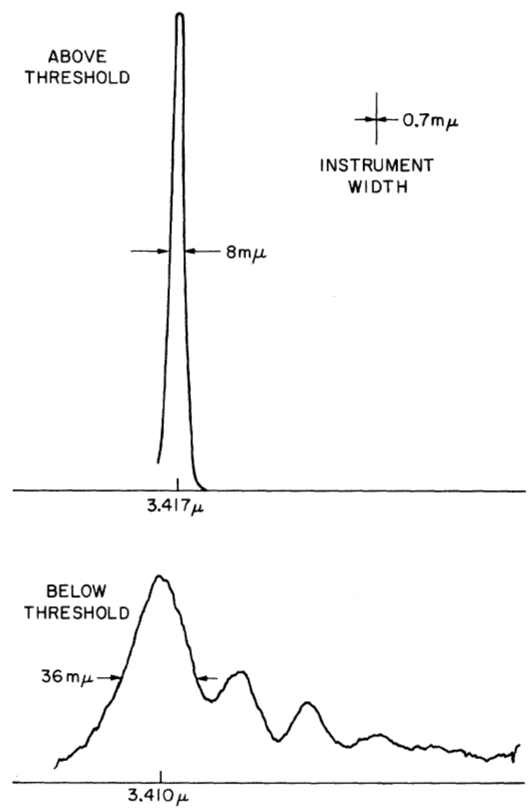
Examples of Linac Capabilities at 25 to 50 MeV

Nuclear Physics: *Fission Modes of* Mg^{24}, A.M. Sandorfi, J.R. Calarco, R.E.Rand and H.A. Schwettman, PRL **45**, 1615 (1980).

- Depended on high duty factor to minimize accidental coincidences.
- Depended on high average current (200μA).
- Depended on small transverse space and small halo to reduce background count rate.

Laser Physics: *First Operation of a Free-Electron Laser,* D.A.G. Deacon, L.R. Elias, J.M.J. Madey, G.J. Ramian, H.A. Schwettman, and T.I. Smith, PRL **38**, 892 (1977).

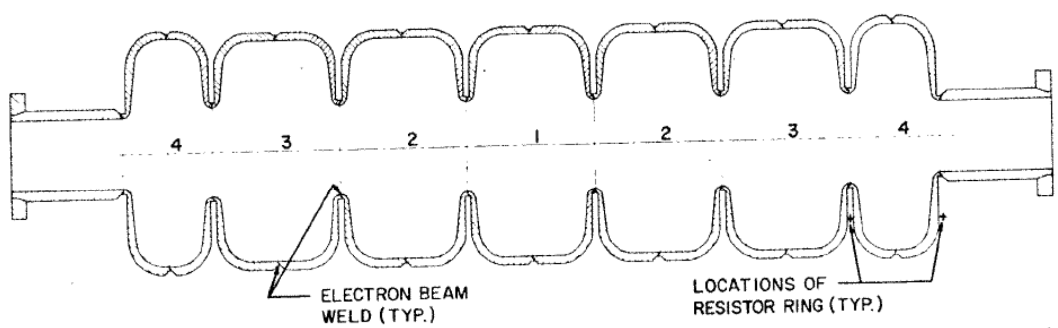




Attacking the Energy Gradient Problem

- Data collected at Stanford and elsewhere indicated that maximum gradient increased with frequency.

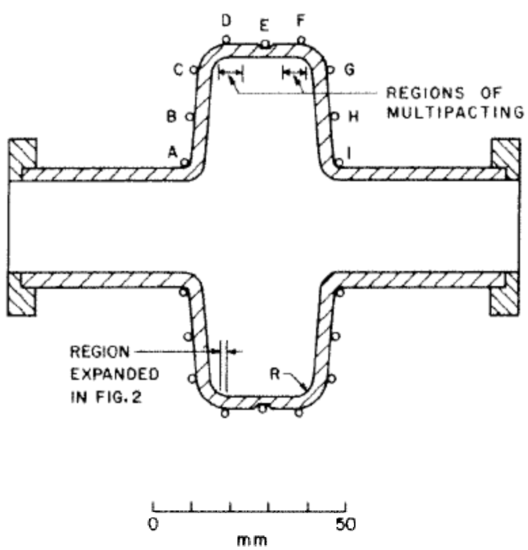
7-cell S-band structures were fabricated and tested giving typical Q-values of $3x10^9$ and energy gradients of 5 MeV/m.



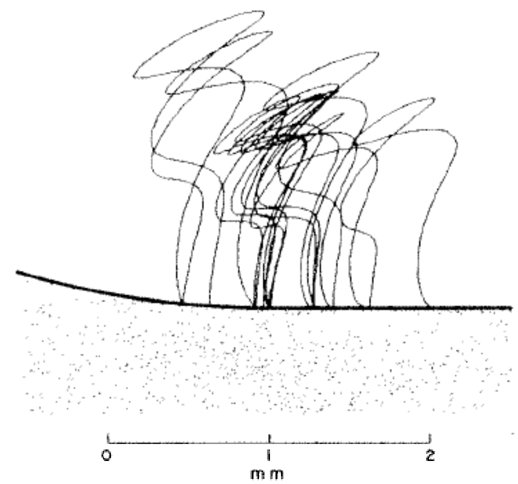
P. Kneisel, C. Lyneis, and J. P. Turneaure, Natural Particle Accelerator Conference, Washington, D.C. (1975).

Attacking the Energy Gradient Problem

- Became clear that ELECTRON MULTIPACTING was a dominating problem in multi-cell structures



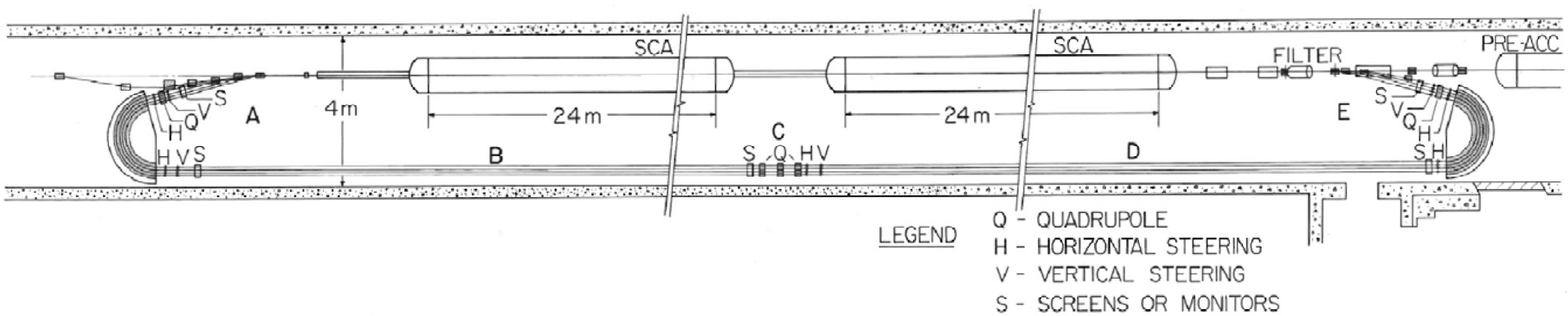
Thermal mapping

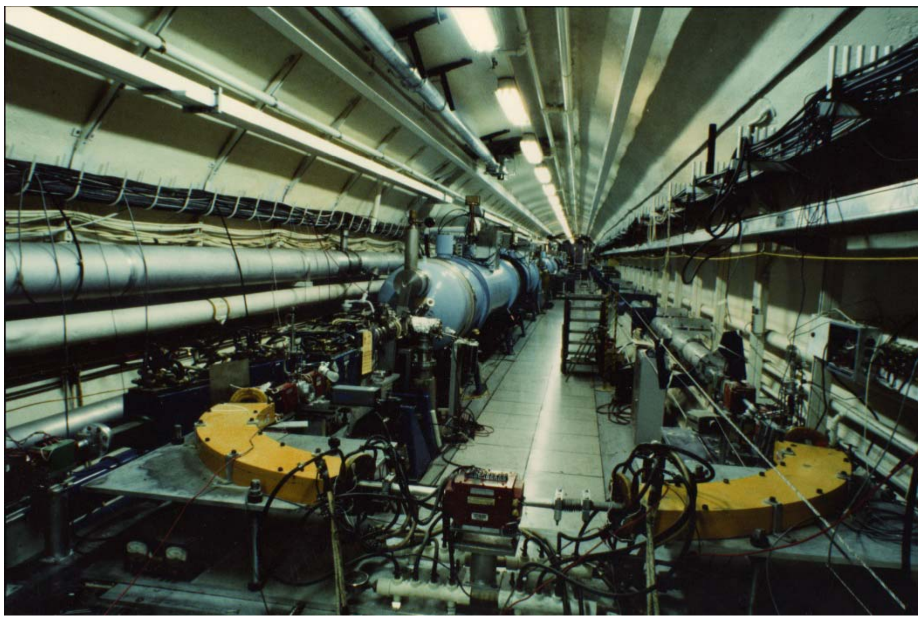


Computer simulation

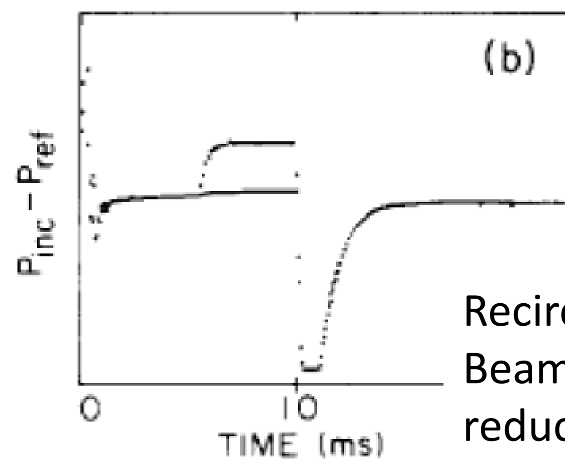
C. M. Lyneis, H. A. Schwettman, J. P. Turneaure, *Appl. Phys. Lett.*, **31**, 541, (1977).

Electron Beam Recirculation





Energy Recovery demonstration



Recirculated Beam phased to reduce required RF drive power

Summary

(1964) First high-field, high-Q SRF cavities.

(1965) First electron acceleration by an SRF cavity.

(1972) First superconducting linear accelerator.

(1976) First Free Electron Laser oscillator.

(1980) First SRF linac with beam recirculation.

(1985) First demonstration of same-cell energy recovery.

(1972)

- Superfluid Helium Refrigerator
- External loading of HOMs
- Feedback Stabilization of Accelerator Fields
- Short π-Mode Structures
- Superconducting Niobium Cavities