Superconducting RF at Cornell

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Outline

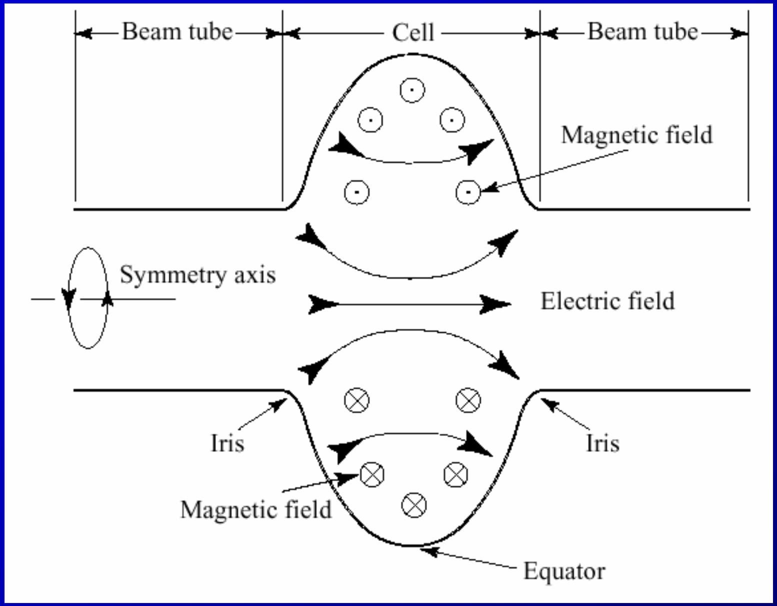
- An Introduction to Superconducting Radio-Frequency (SRF)
- The Struggle for high Fields
- SRF for future Machines around the World
- SRF at Cornell
- SRF Tour

An Introduction to

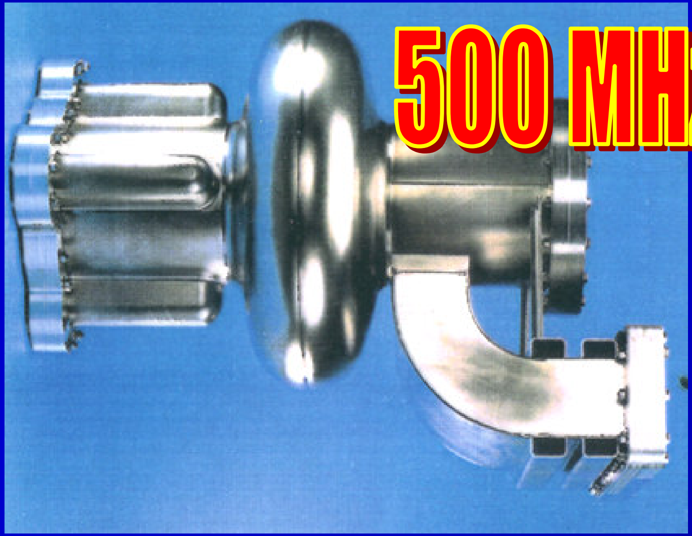
Superconducting Radio-Frequency (SRF)

SRF Cavities

- Material: **Niobium**, T_c = 9.2K
- Use EM fields (RF-fields) in cavities for acceleration.
- **Lowest frequency eigen-mode** has a longitudinal electric field → use this mode for **acceleration**
- Typical RF frequency: **0.5 GHz to 1.5 GHz**
- **Higher-Order** (higher frequency) **modes**: unwanted → need **damping**



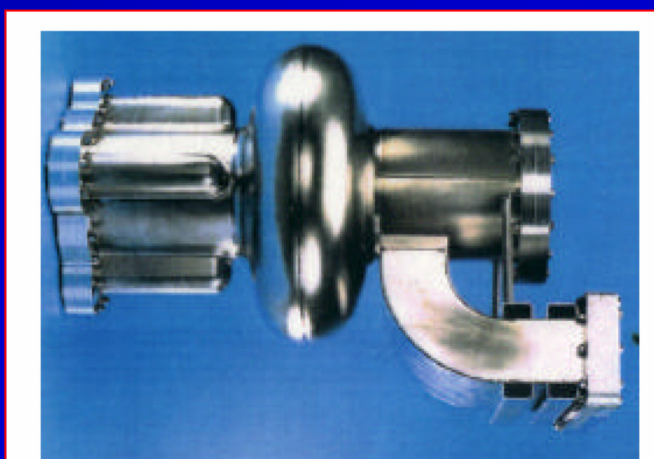
SRF Cavities at Cornell

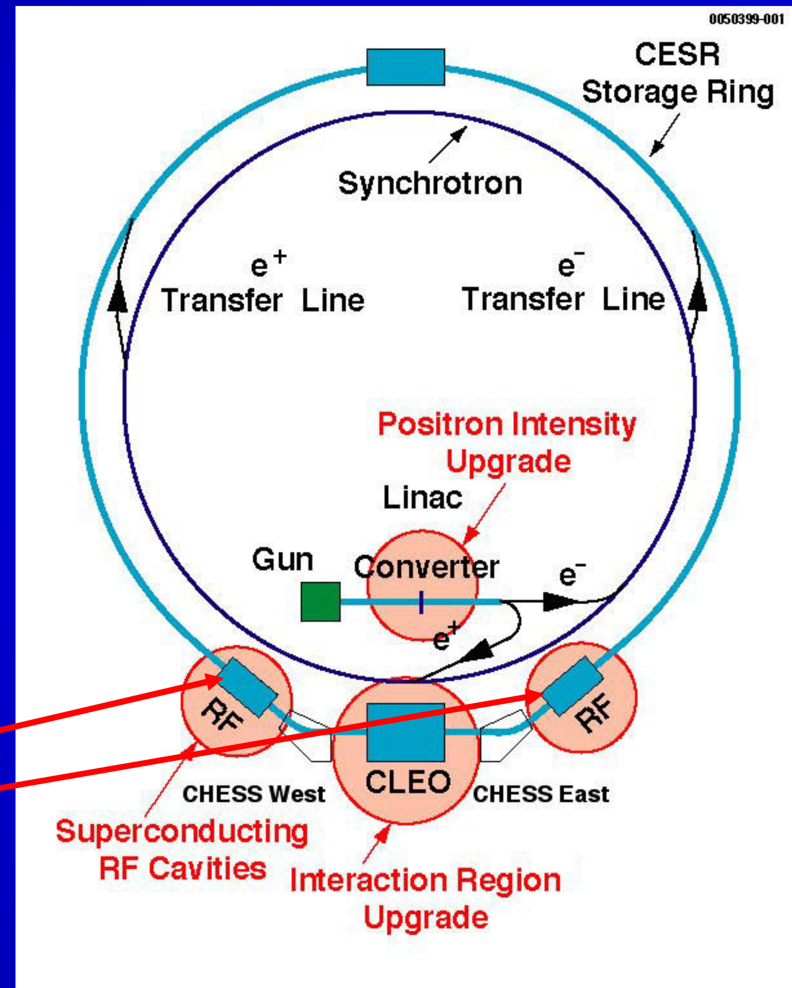


SRF Cavities at Cornell: CESR

Example: CESR

Challenge is to store high currents stably (ampere) rather than achieve very high energy

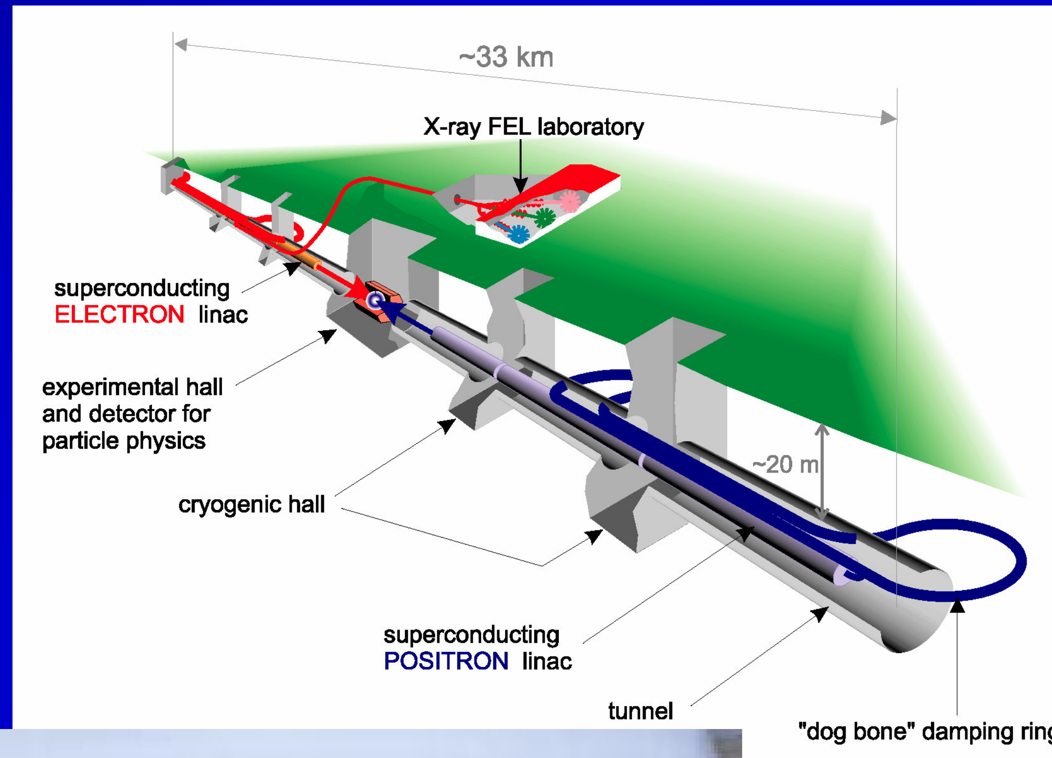




SRF Cavities: Engine for Accelerators

Example: ILC

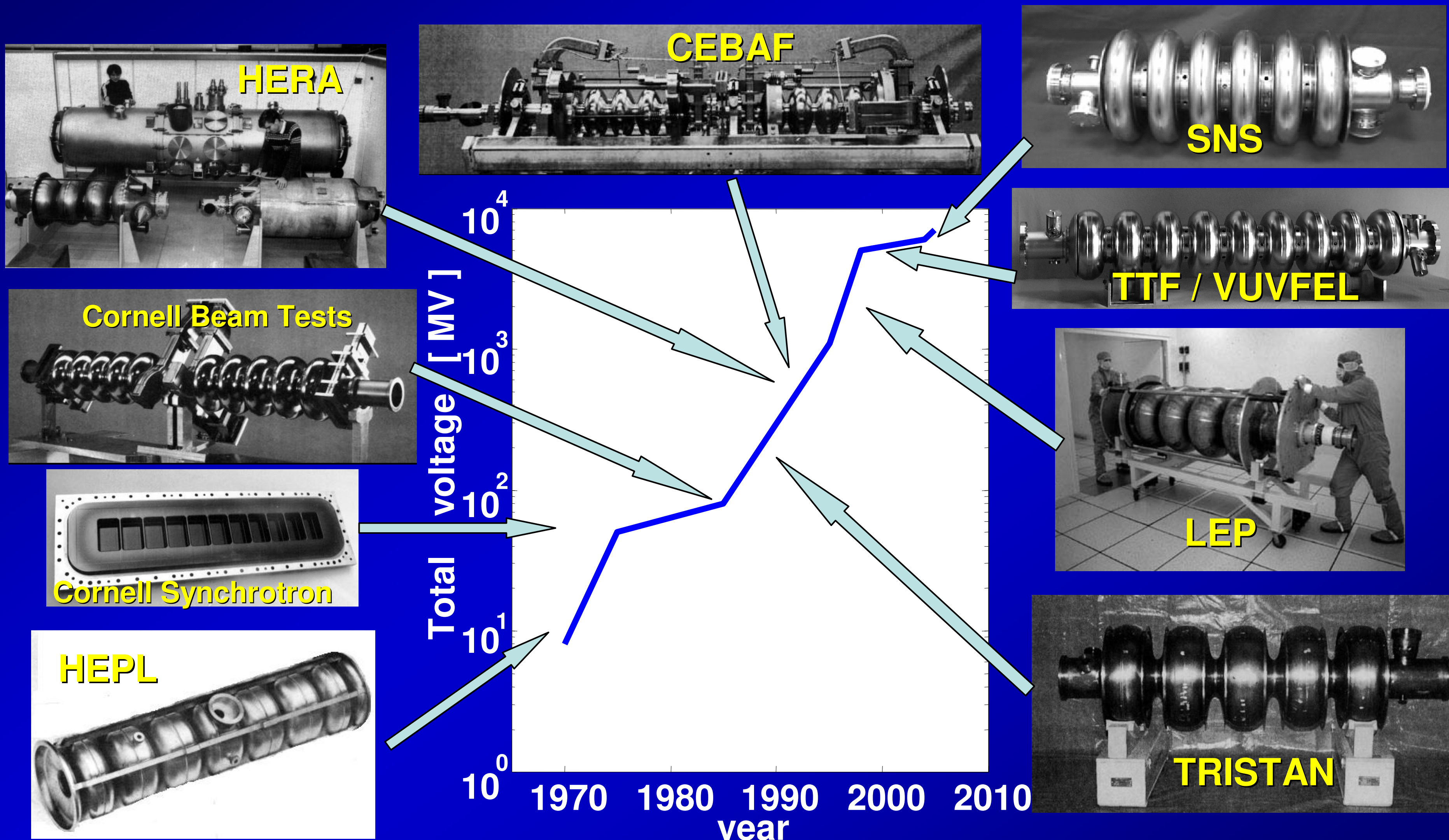
Challenge is to reach very high energy while maintaining good beam quality!



>20,000 cavities!

500 GeV cm energy

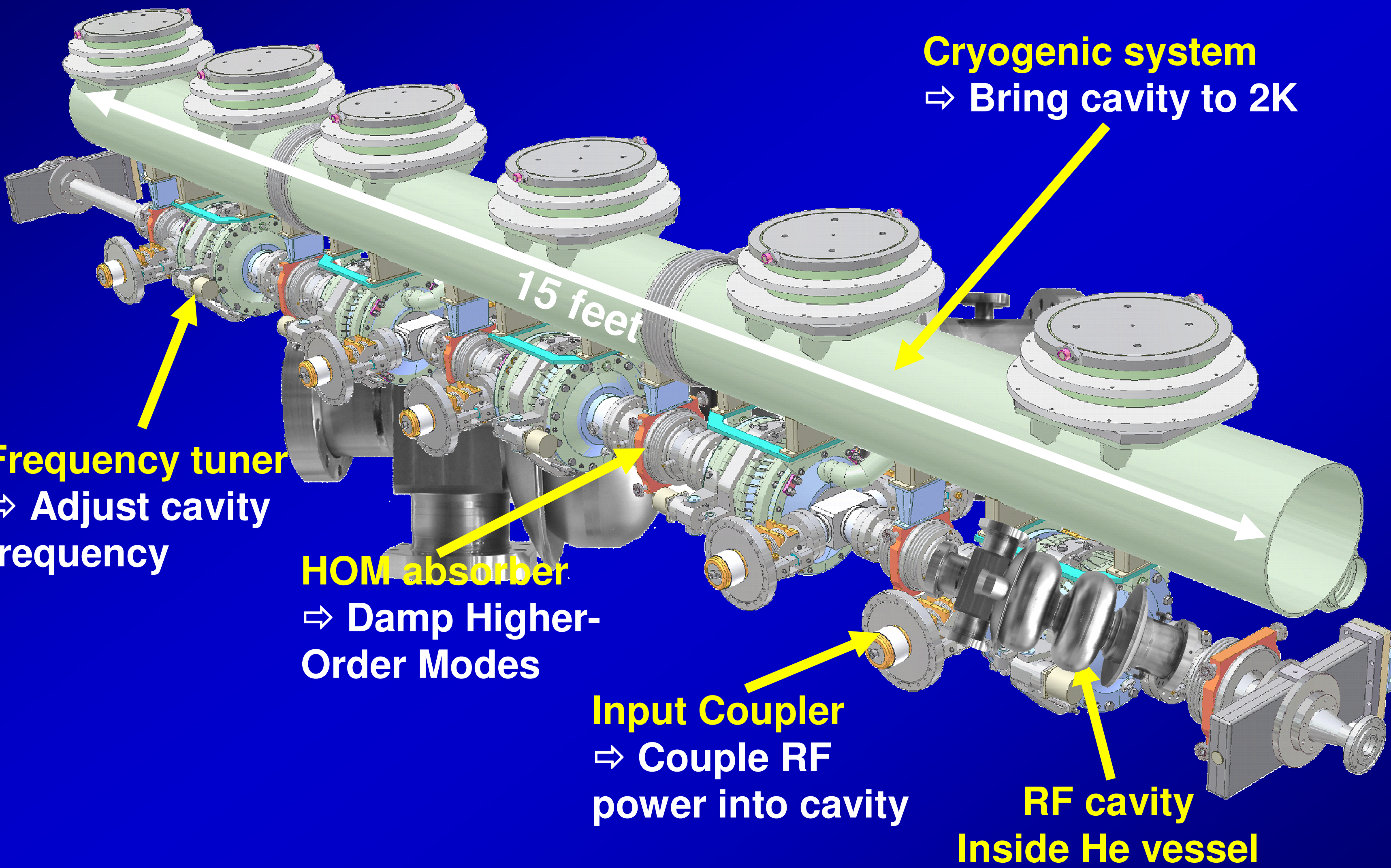
A rapid Growth in SRF Application



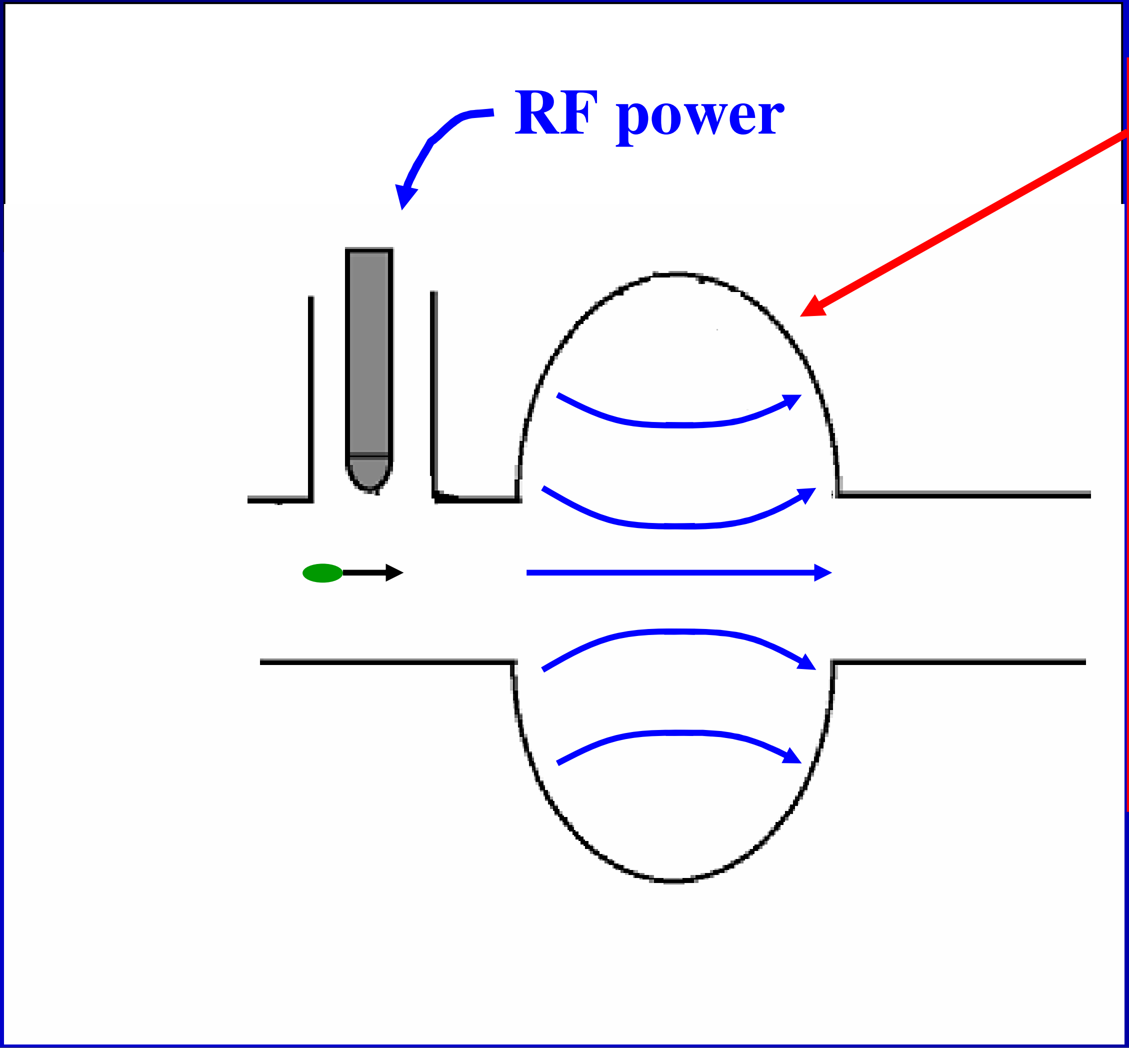
A Science makes Science

- **SRF for high-energy-physics:**
  - TRISTAN, HERA, CESR, LEP, SPS, KEK-B
- **SRF for nuclear science:**
  - CEBAF, ATLAS, SBSL, Florida State U., PIAVE, JAERI, New Delhi, CEN Saclay, Australian National U., U. Of Washington, …
- **SRF for neutron sources:**
  - SNS
- **SRF for Free-Electron-Lasers:**
  - DESY VUV-FEL, TJANF IR-FEL, ELBE, …
- **SRF for storage ring light sources:**
  - CHESS, Diamond, Canadian LS, Taiwan LS

From a Cavity to a whole SRF Cryomodule: The SRF Booster Module for the ERL



Why superconducting? Wall Losses



<u>Wall losses:</u>

Surface currents ($\propto H$) result in dissipation proportional to the surface resistance (R_s):

$$\frac{dP_{diss}}{ds} = \frac{1}{2} R_s \left| \vec{H} \right|^2$$

Why Superconducting Cavities?

Accelerating Mode:

$$Q_0 = \frac{f}{bandwidth} \propto \frac{1}{R_S}$$

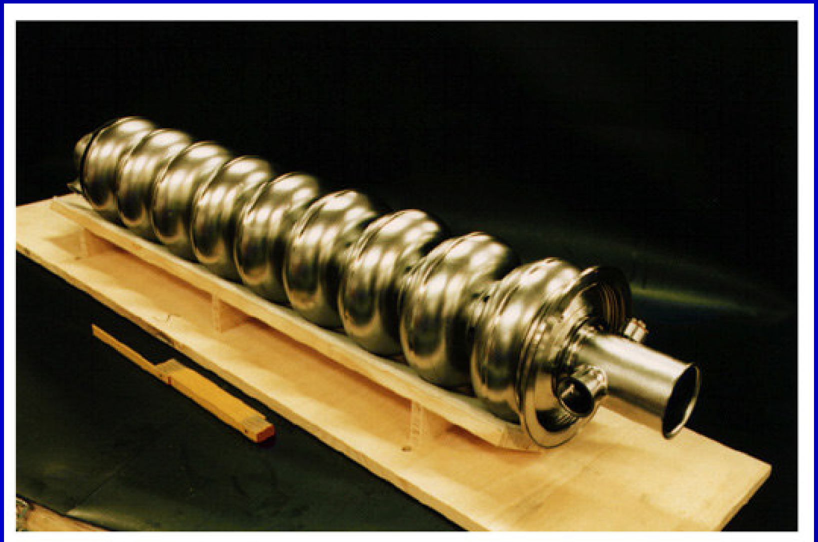
- Superconductor ⇨ very small RF losses
- Q_0: includes RF wall losses only
  - ⇨ Very high quality factor Q_0
  - ⇨ Typical: $Q_0 \approx 10^{10}$!
  - ⇨ V=20MV ⇨ P_{SRF}=15W
  - ⇨ Normal-conducting: $Q_0 \approx 10^4$ ⇨ P_{nc}=15MW

Why SRF and not normal-conducting RF?

Advantages of superconducting RF cavities:

- ***Much lower wall losses (6 orders of magnitude)!***
  - ⇨ Lower operating costs.
  - ⇨ Can operate at a higher voltage in cw operation or long pulse operation. ⇨ Fewer cavities means less beam distortion.
  - ⇨ Freedom to tailor cavity design to specific accelerator requirements (Power dissipation is not the primary concern!) ⇨ Better beam quality. Higher beam currents.
    - ⇨ Example: Beam current in CESR more than doubled by replacing all copper cavities with superconducting cavities.!

Superconducting vs. Normal Conducting Cavity



- one cell from NLC
- normal conducting cavity
- copper
- 11.4 GHz
- water cooled

- TESLA
- superconducting cavity
- niobium
- 1.3 GHz
- 2 K (LHe)

Fundamental differences due to difference in wall losses.

RF Superconductivity (I)

- RF resistance small but finite because Cooper pairs have inertia.
  ⇨ nc electrons "see" an electric field!
- BCS theory: Frequency and temperature dependence of surface resistance at low RF fields (T_c: S.c. transition temperature)

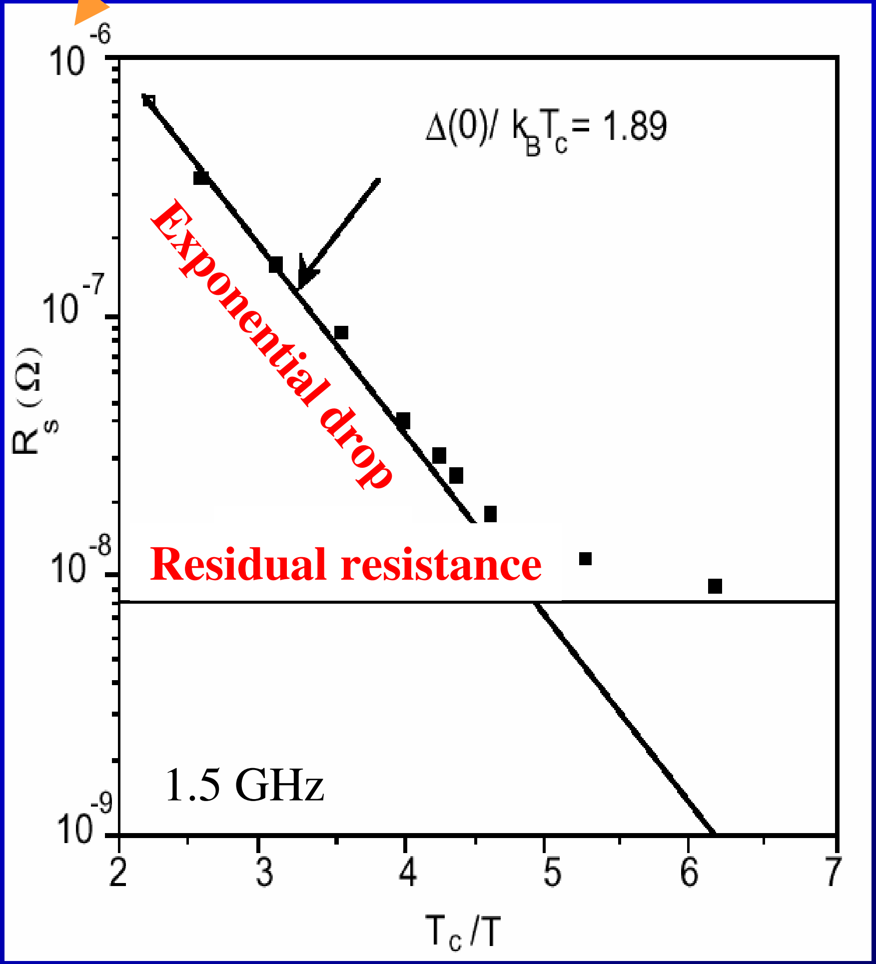
$$R_{BCS} \propto f^2 e^{(-const*T_C/T)}$$

More resistance the more the electrons are jiggled around.

More resistance the more nc electrons are excited.

- Real live: $R_s = R_{BCS} + R_{RES}$

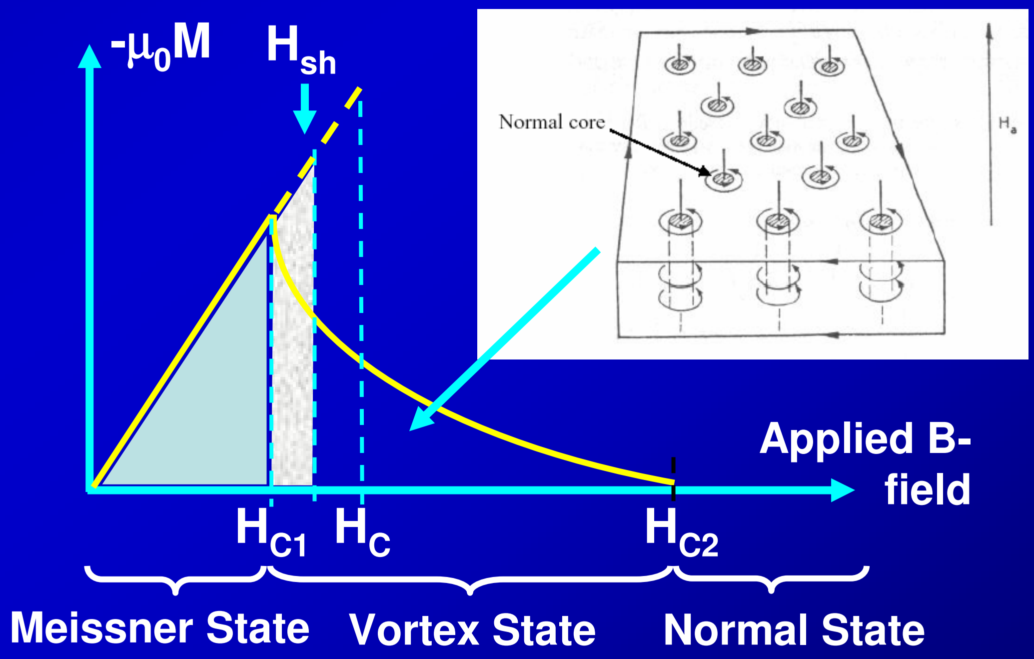
Compare with Cu: R_s ~ 10 mΩ



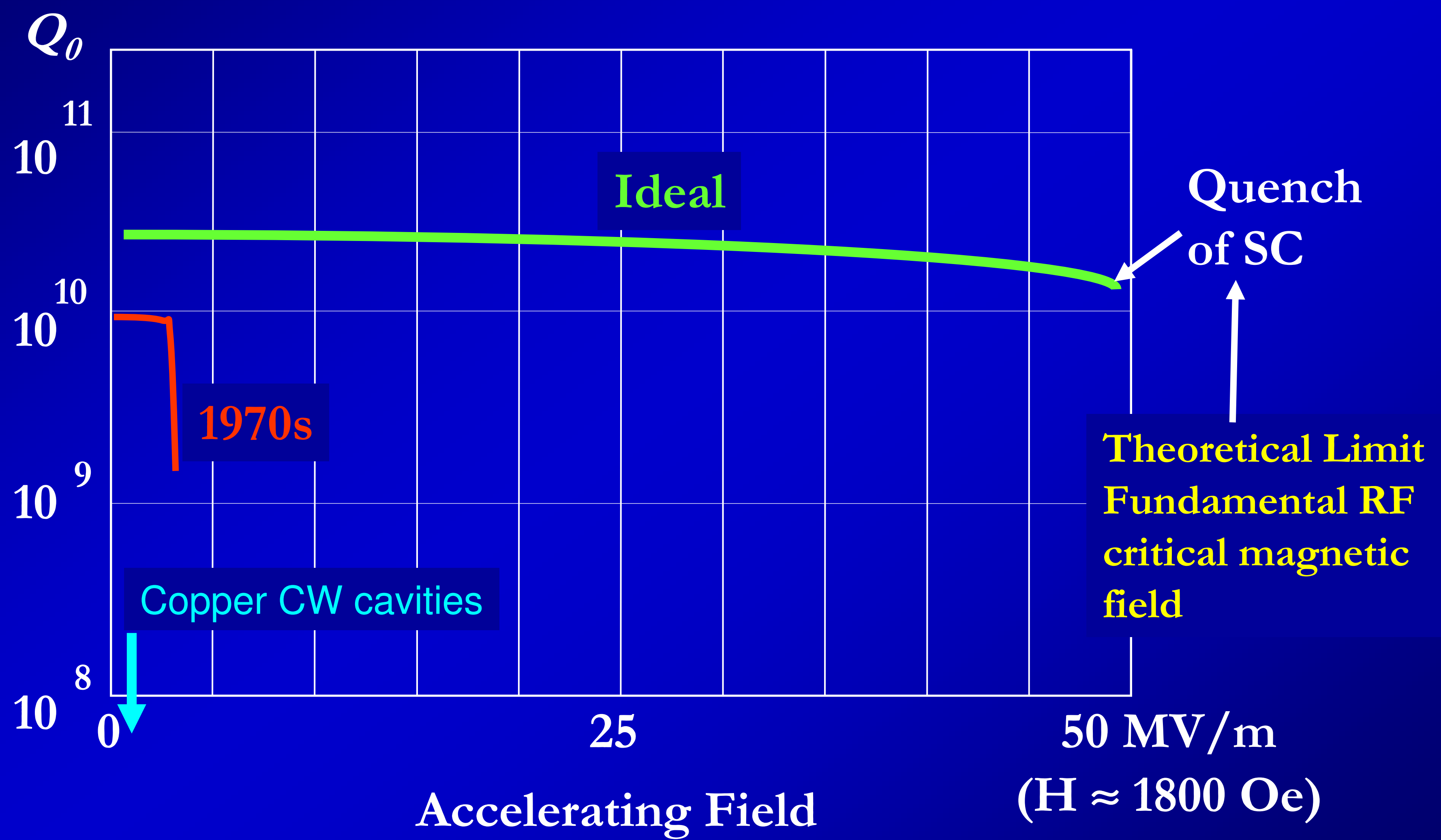
RF Superconductivity (II)

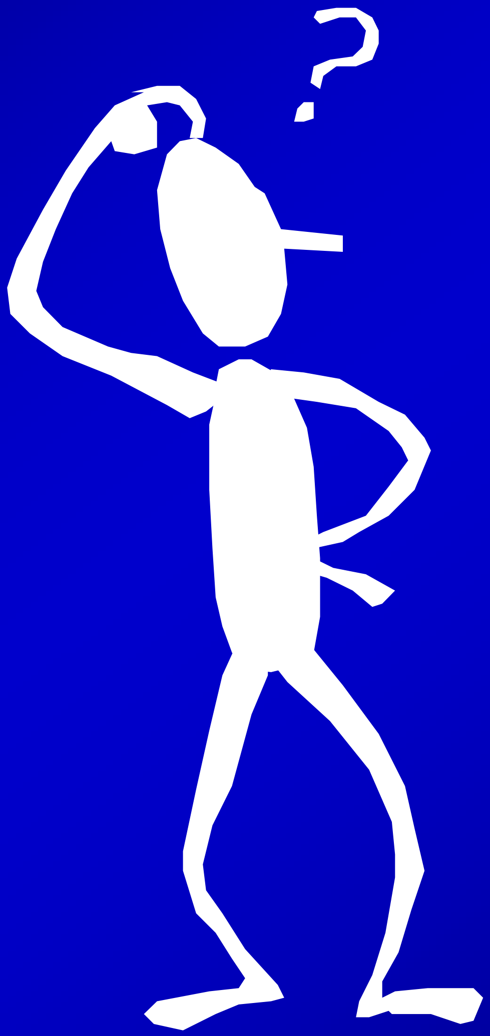
- <u>Critical magnetic RF field</u> limits maximum achievable field in a SRF cavity.
- But: What is the critical <u>RF field</u>?
- Niobium: Weak type II superconductor
- Measured: Meissner state can persist meta-stably above H_{c1} in RF fields (superheating field H_{sh})
- But: How far above H_{c1} is the open question! Theory??

Type II Superconductor



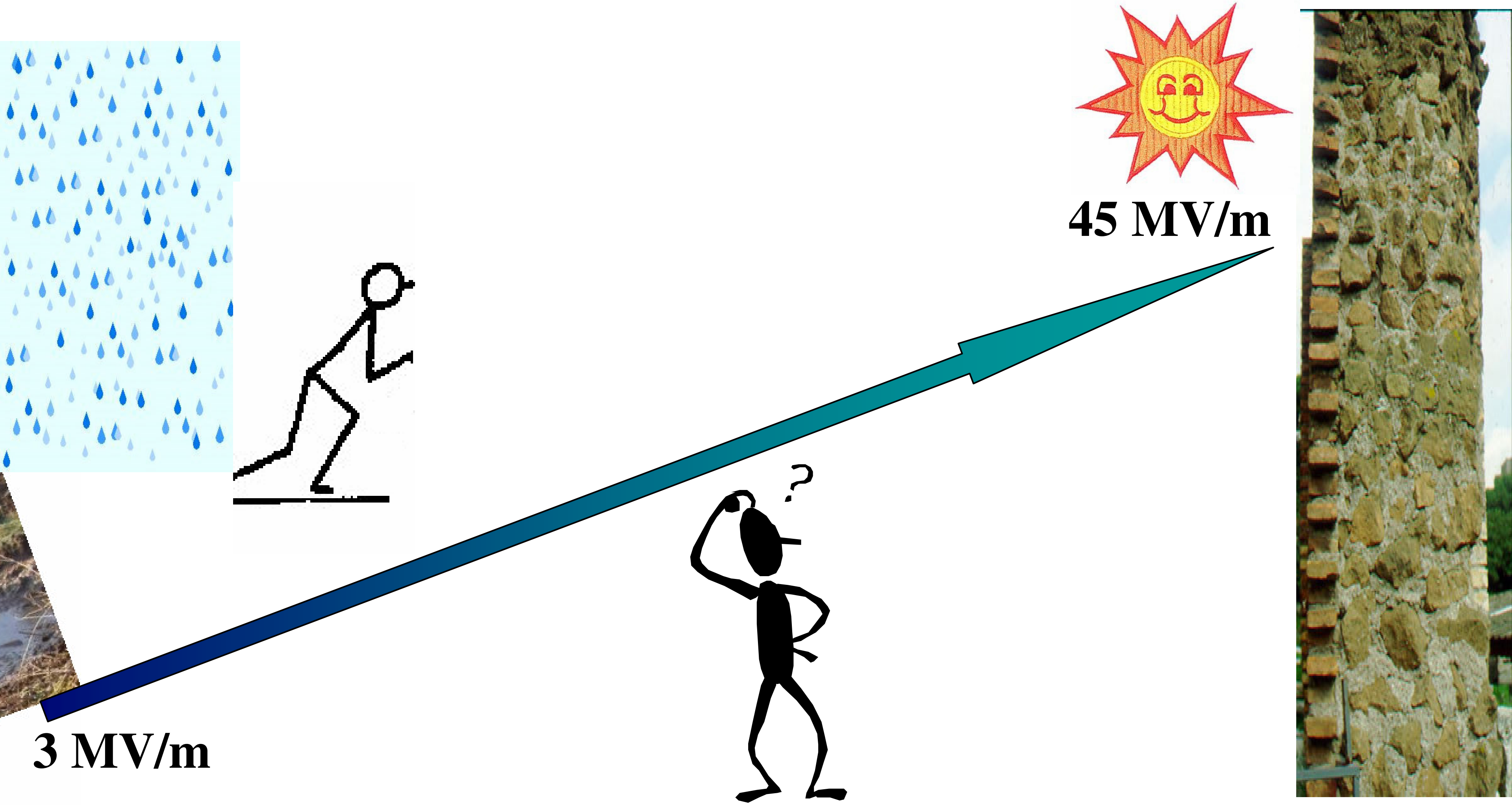
Ideal and Real Cavity Behavior





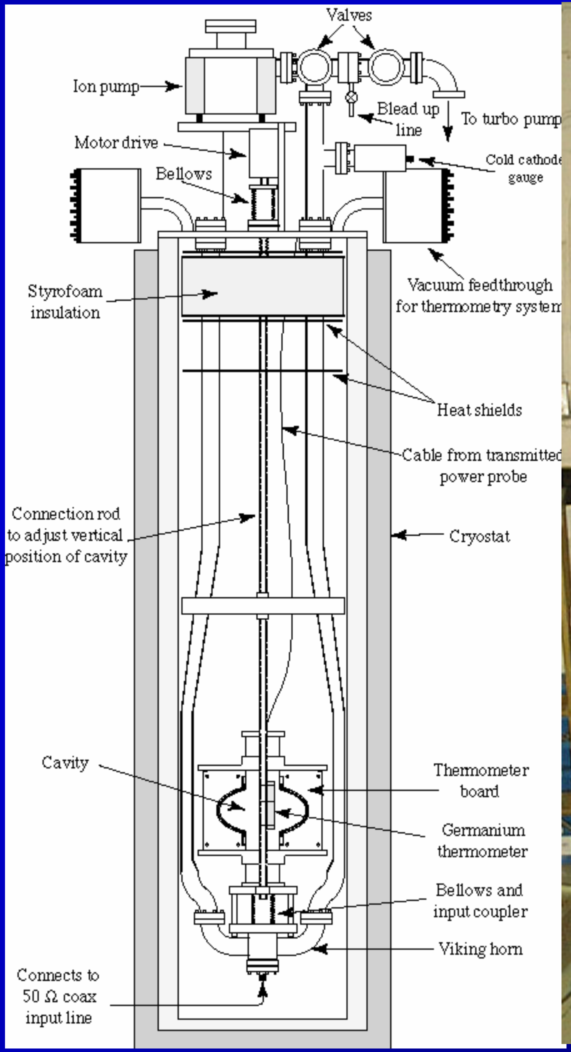
The Struggle for high Fields

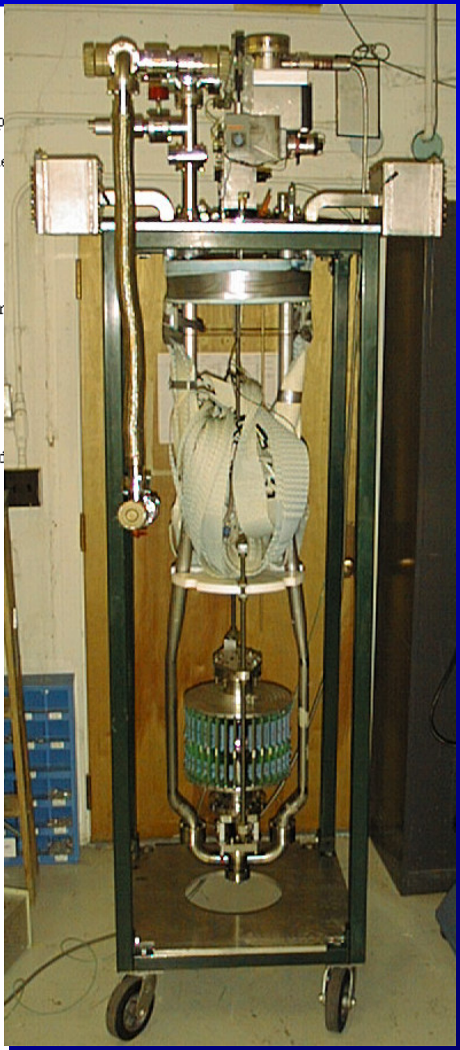
The Real World…



Vertical Cavity Tests

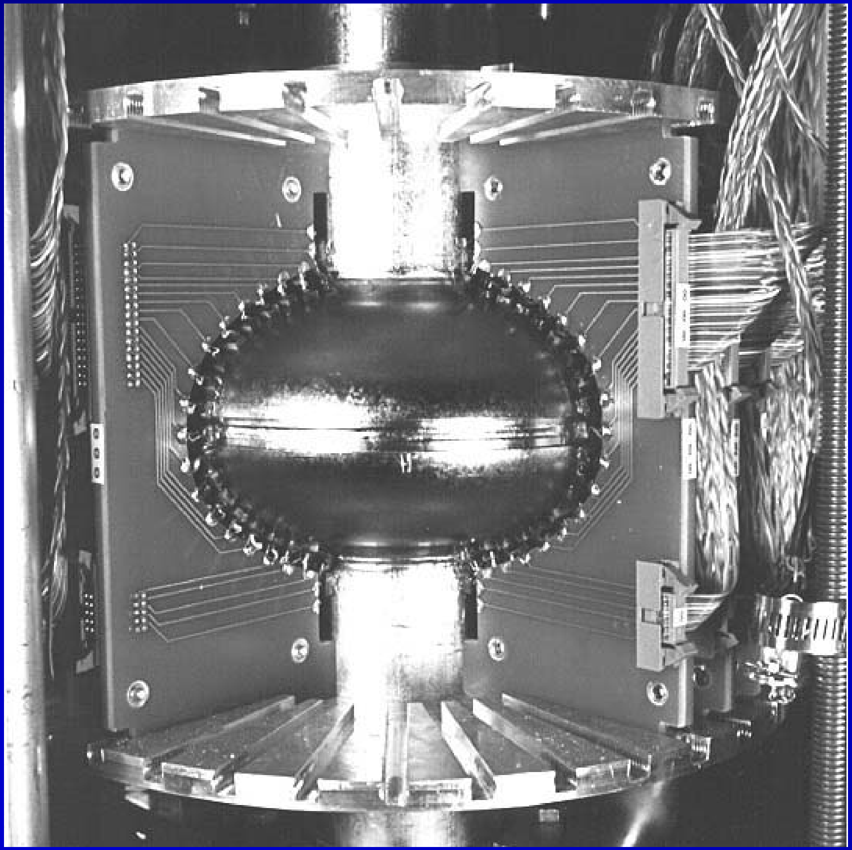
- Work horse of cavity studies is the vertical test arrangement.
- **Measure Q_0 (wall losses) v. E_{acc}**
- **It permits rapid turnaround for tests.**

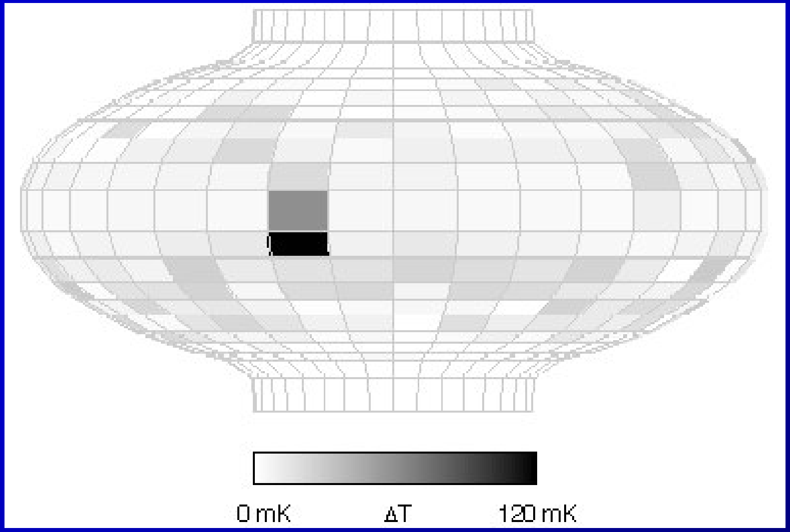




Thermometry

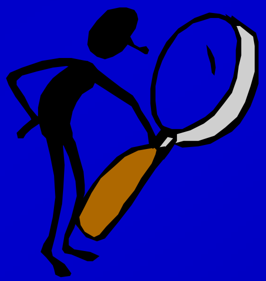
- Cover cavity exterior with special thermometers to detect heat dissipated by defects

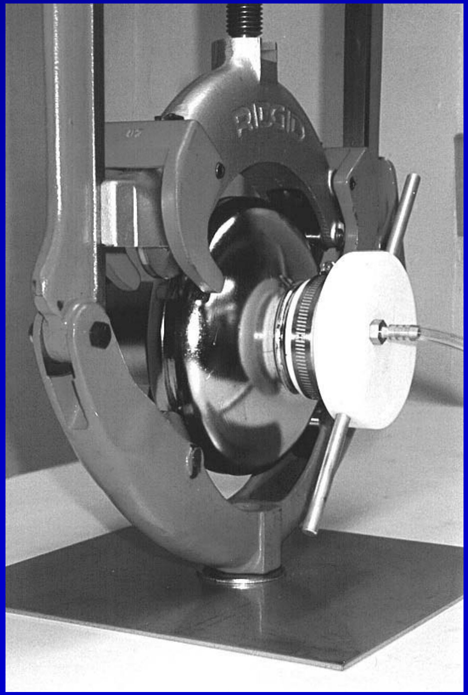




Microscopy

- Use an SEM and Auger Analysis to examine the cavity interior.





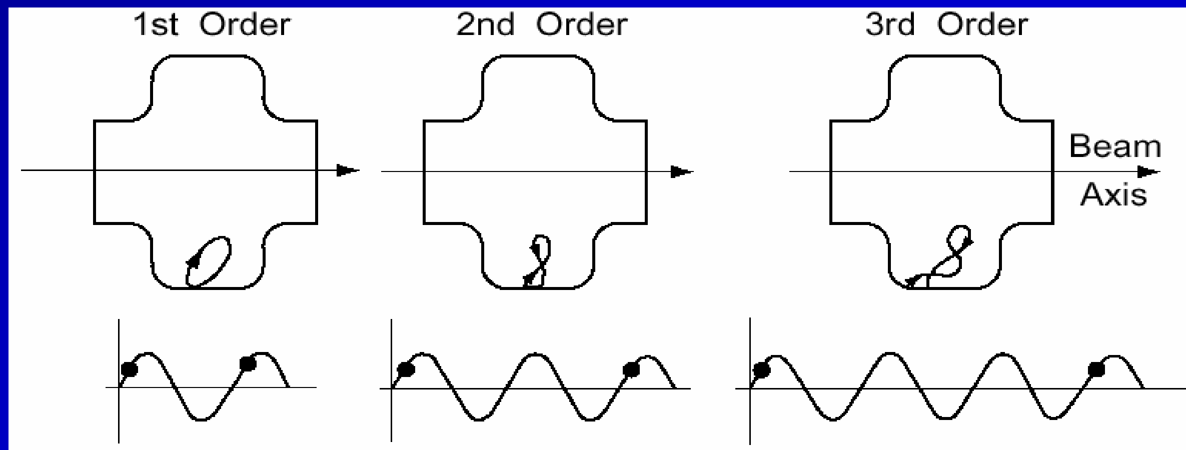
Evolution of SRF Cavity Field Gradients

	1975 3 MV/m	1985 6 MV/m	1990 15 MV/m	1995 25 MV/m	2005 >40 MV/m
Limitation:	Electron multiplication	Thermal breakdown	Electron field emission	High field Q-reduction	
Solution:	Improved cavity shape	High-purity Nb	High-pressure rinsing	Electropolishing, high and low temperature baking, …	

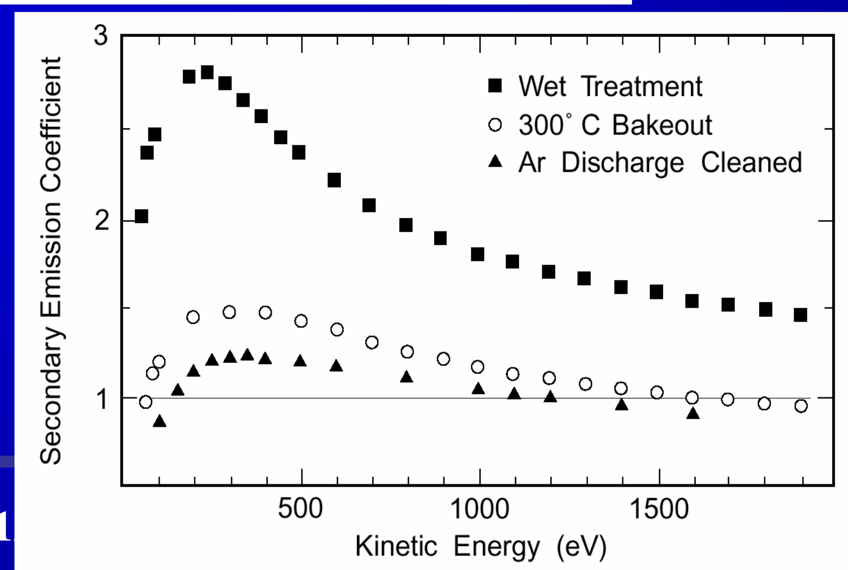
⇨ Cornell has been prominent in overcoming all these limitations

Problem 1: Multipacting (1970s)

- MP is due to an exponential increase of electrons under certain resonance conditions:

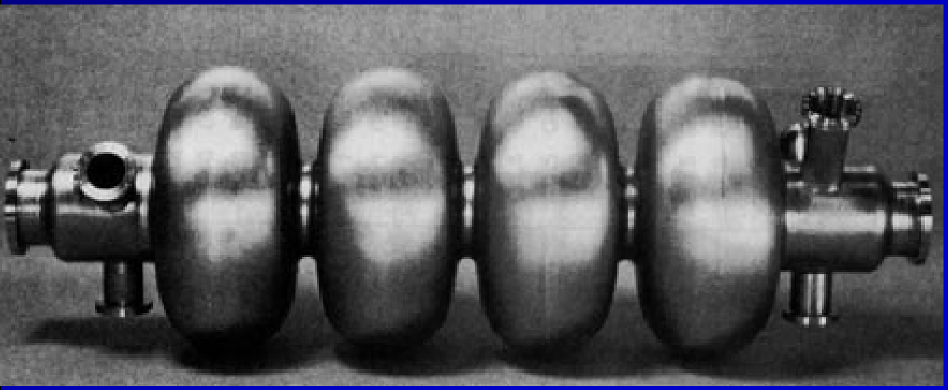


- Not all potential barriers are active because electron multiplication has to exceed unity.

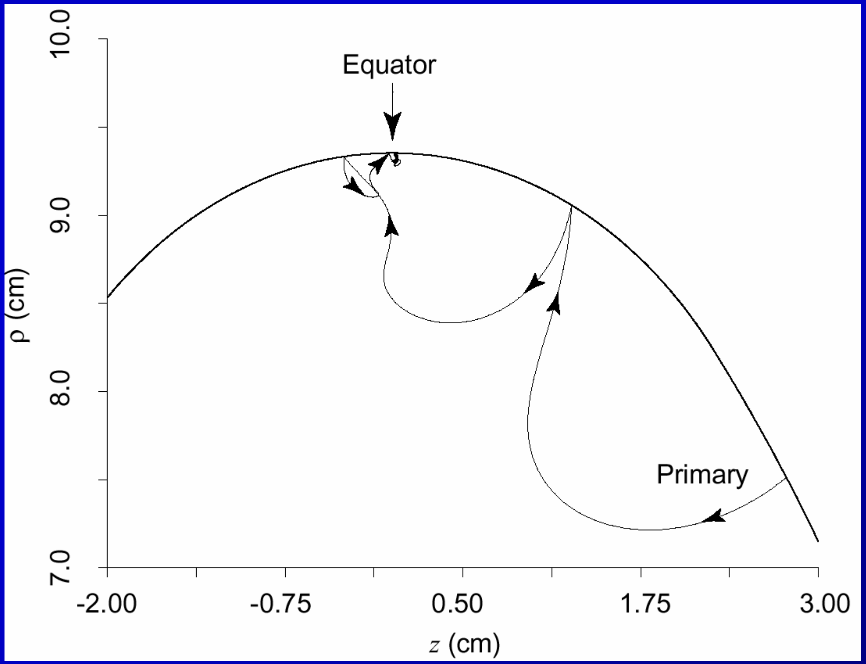


Multipacting: Solution

- In cavities, solved multipacting by adopting a elliptical cell shape:



350-MHz LEP-II cavity (CERN)



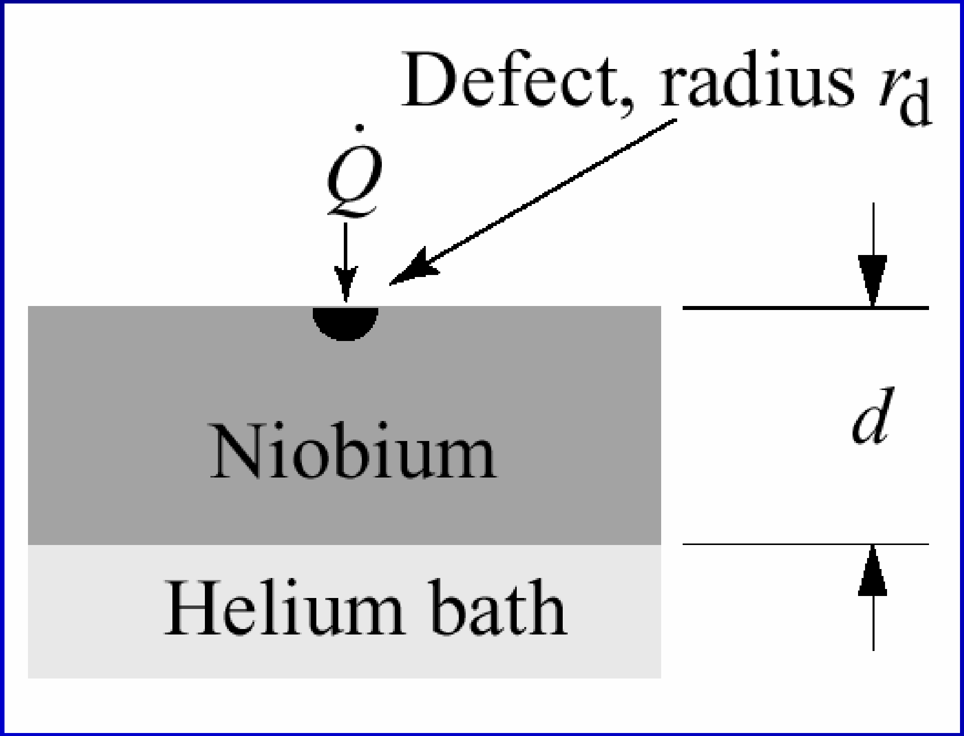
Electrons drift to equator, where electric filed is ≈ 0.

⇒ MP electrons don't gain energy.

⇒ MP stops.

Problem 2: Thermal Breakdown (1980s)

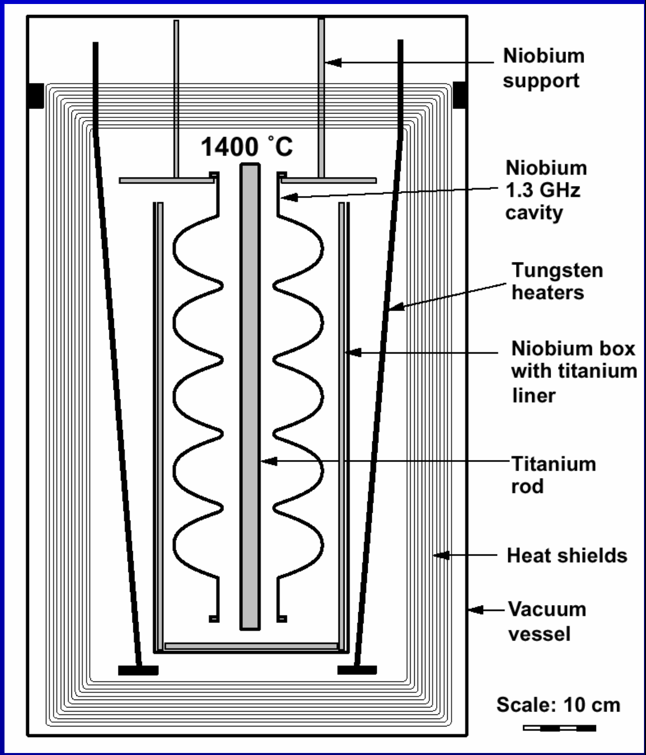
- Thermal breakdown (quench) is usually triggered by a normal conducting defect, when it heats the Nb above the critical temperature.



0.1 – 1 mm size particles can cause TB!

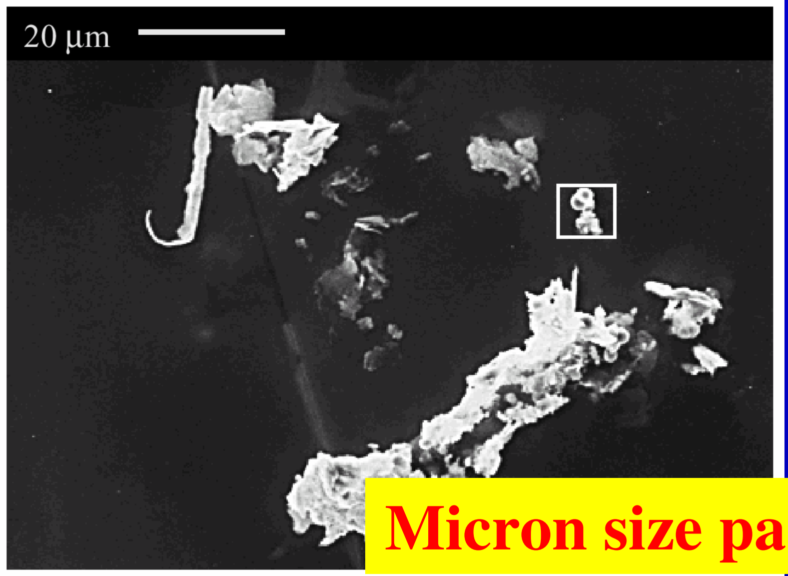
Thermal Breakdown: Solutions

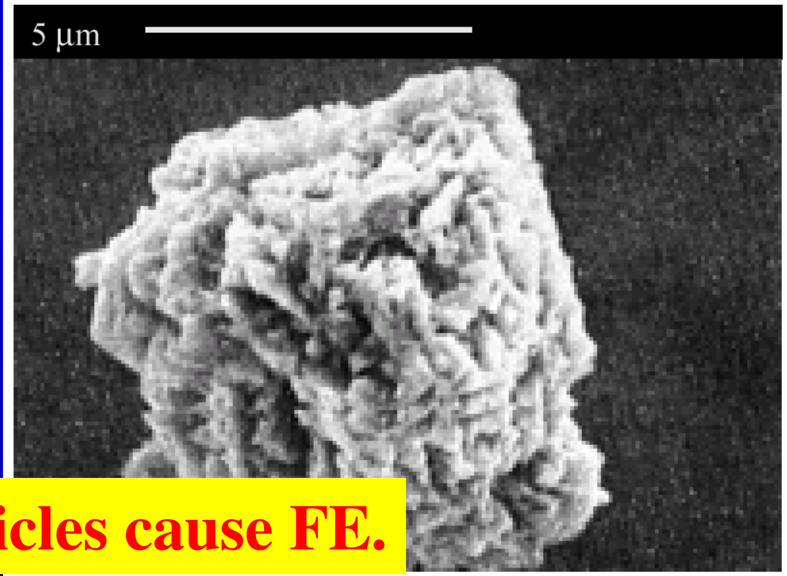
- **Avoid defects:**
  - ⇨ Clean niobium and cavity production.
  - ⇨ Clean assembly.
- **Tolerate unavoidable defects but "neutralize" them by thermally stabilizing them.**
  - ⇨ Improve the thermal conductivity of niobium.
  - ⇨ Improve purity of the niobium.



Problem 3: Field Emission (1990s)

- Emission of e^- from cavity surface in high E-fields.
- All emission is associated with (conducting) microscopic particles.
- Acceleration of electrons drains cavity energy.
- Impacting electrons produce heating of the surface.





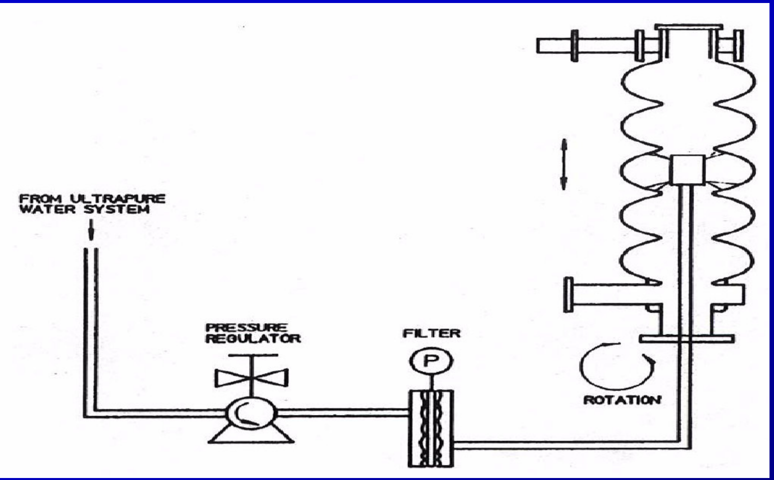
Micron size particles cause FE.

Field Emission: Solutions (I)

- ***Buffered Chemical Polishing (BCP):***
  - ➢ **Etching removes damaged surface layer (100 μm)**

$BCP = HF + HNO_3 + H_3PO_4$

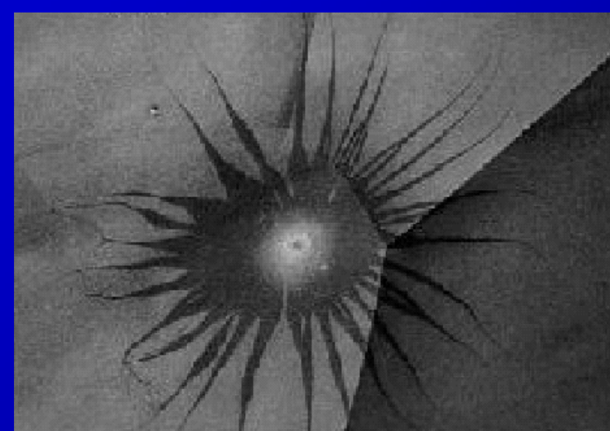
- ***High Pressure Water Rinsing (HPR):***
  - ➢ **Rinsing of cavities with up to 1000 psi ultra-pure water jets removes many particles.**



Field Emission: Solutions (II)

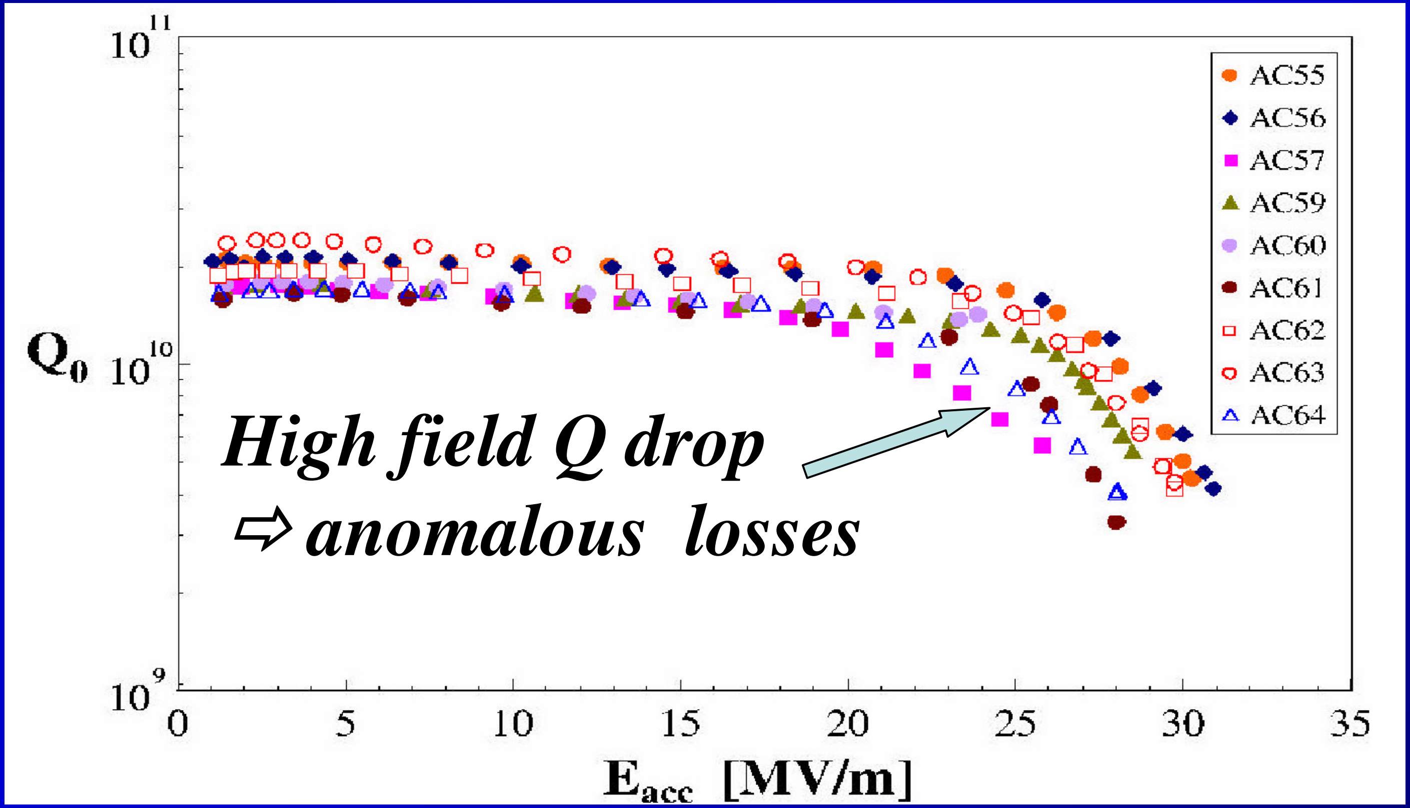
- ***Clean Room Technology:***
  - **All cavities and vacuum components are cleaned and assembled in clean rooms.**
- ***High-Power Processing:***
  - **In some cases applying of high power can cause the destruction of field emitters and improve the cavity performance.**

⇨ Reduction of field emission after the cavity is installed in the accelerator



Problem 4: High Field Q-Reduction (>1995)

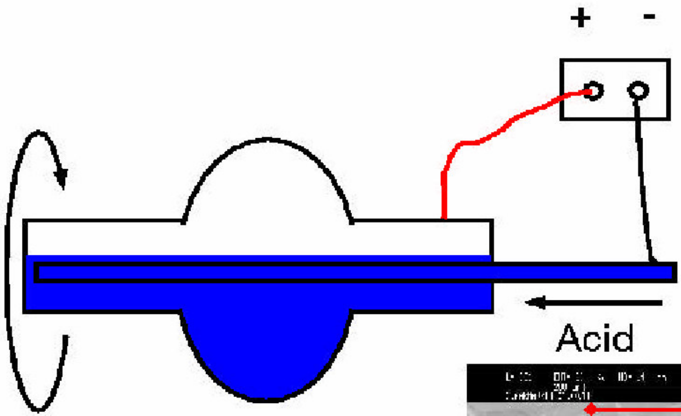
- High field Q-slope without field-emission!
- Effect not 100% clear yet…



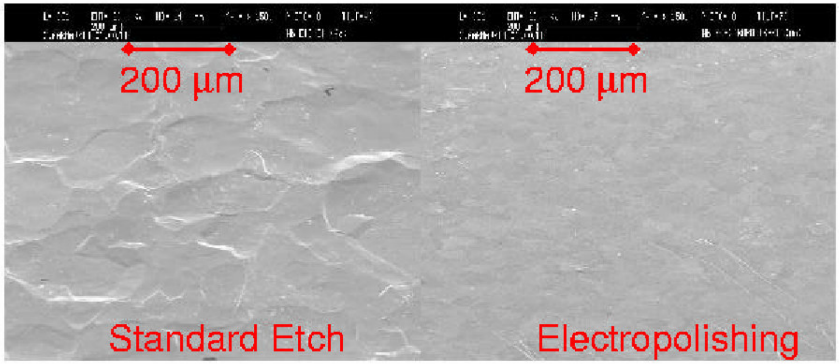
High Field Q-Reduction: Solution

- *Electropolishing of cavities*

Electropolishing of 1-cell cavities (Scheme)



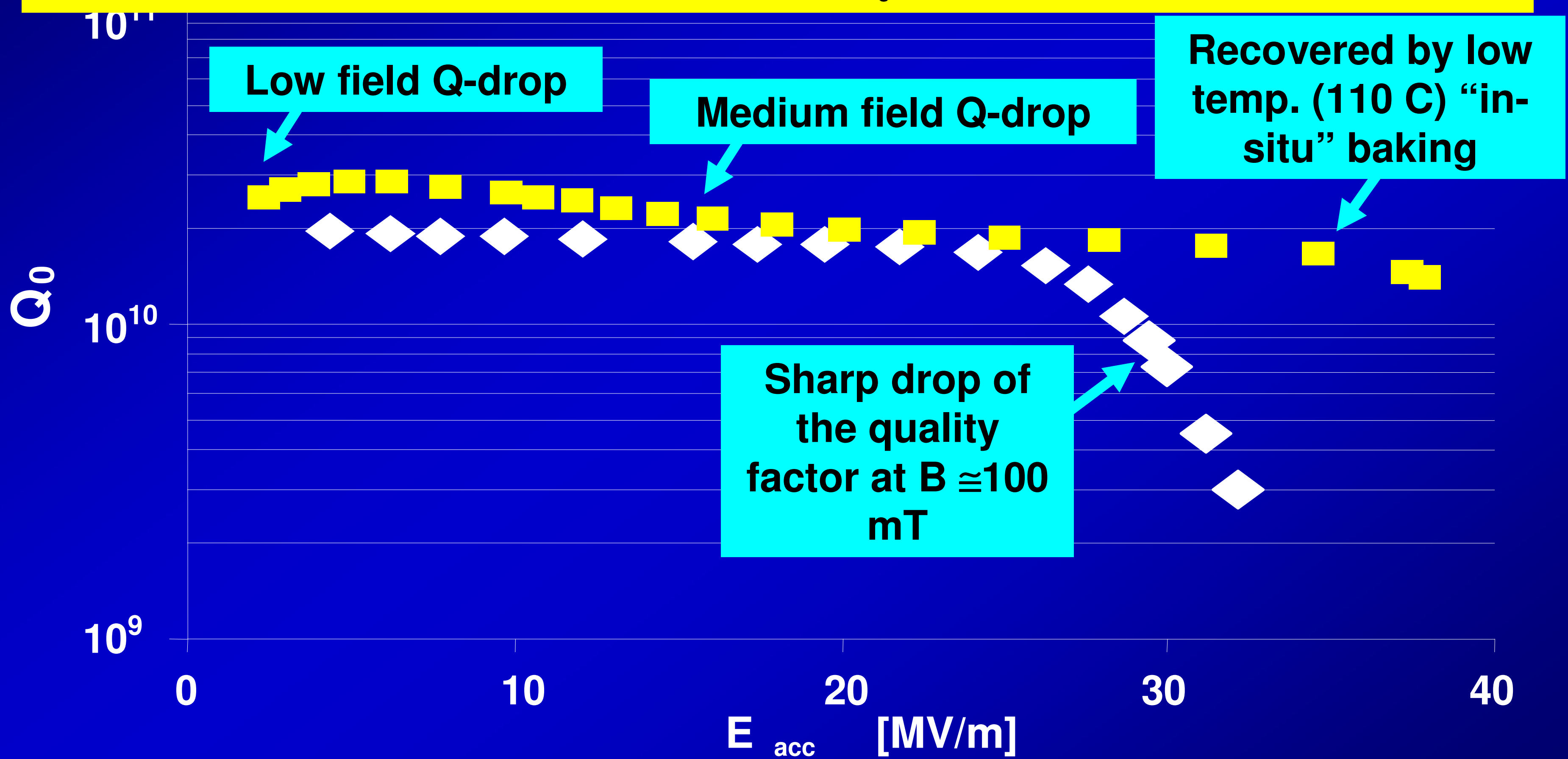
- EP electrolyte
- 90 % H_2SO_4
- 10 % HF
- 30 °C
- 0,5 µm/min removal of material



- *Low temperature (110 C) "in-situ" baking*

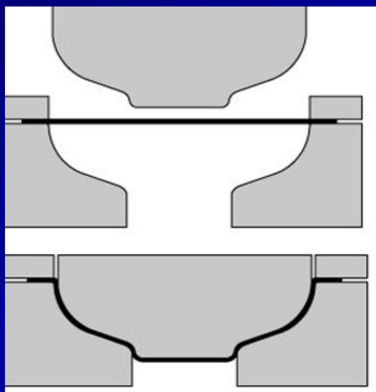
State of the Art Cavity Performance

We know how to make good Nb cavities, but we don't understand well why it works…

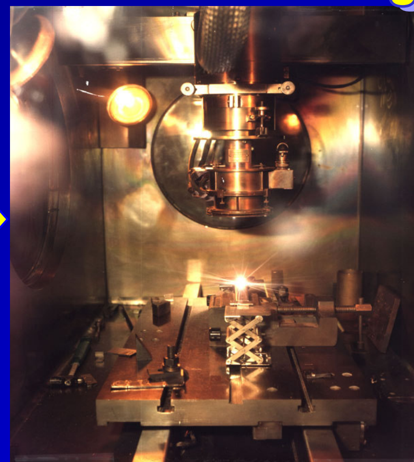


How to get high fields? A Recipe

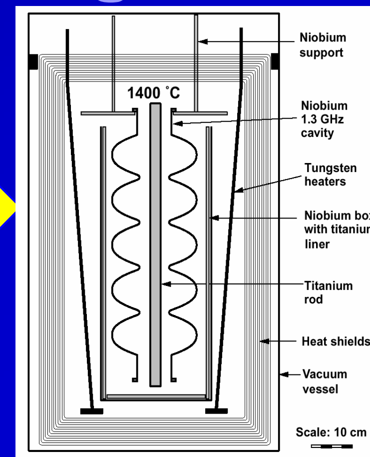
Stamping



Ebeam Welding



High T bake



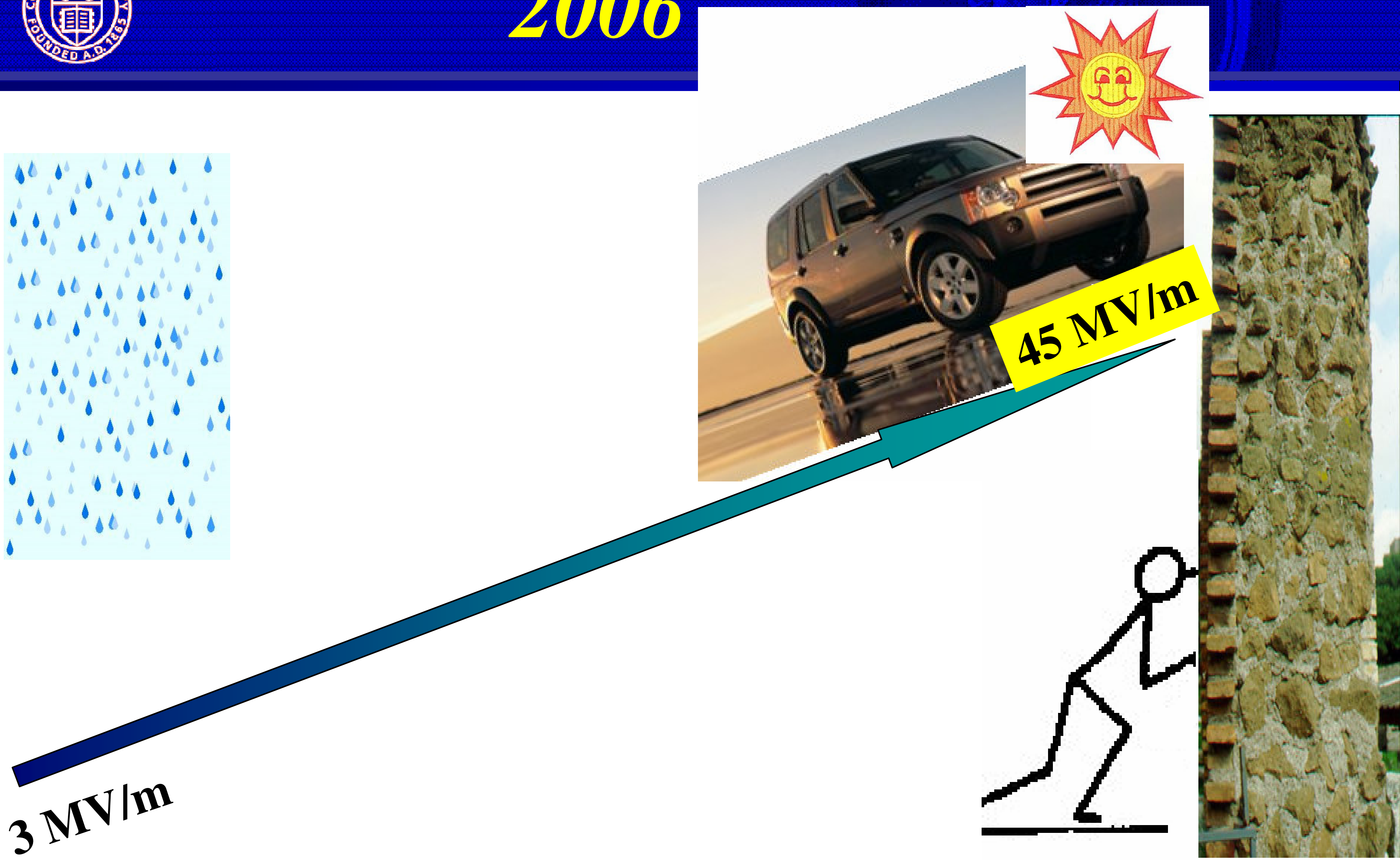
Chemical Etching

High Pressure Rinsing

Mounting in Clean Room

110C bake

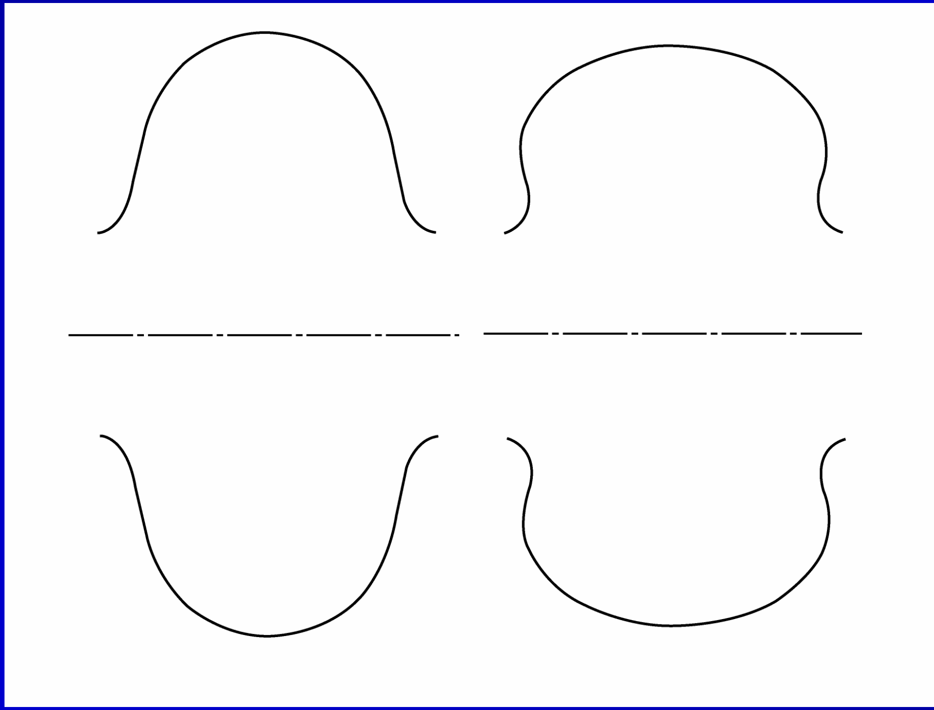
2006



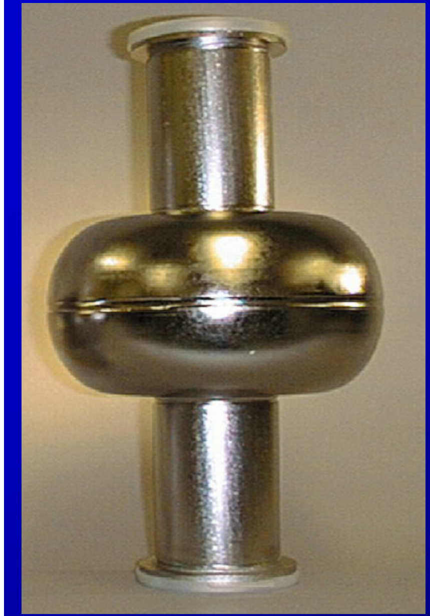
Reentrant Cavity Shape

old

$$\frac{H_{pk}}{E_{acc}} = 42$$

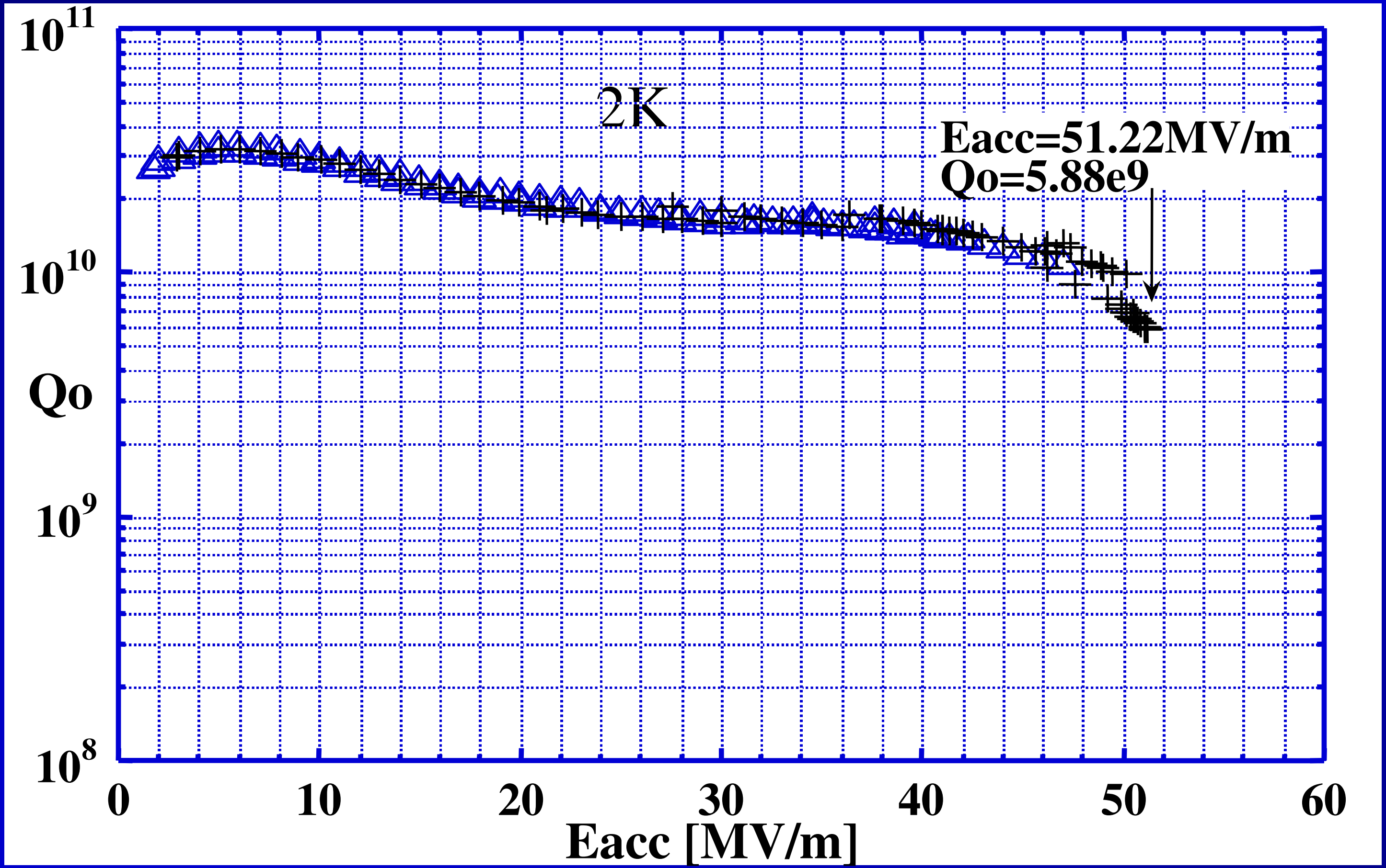


new



$$\frac{H_{pk}}{E_{acc}} = 37.8$$

Reentrant Cavity: World Record Gradient



Cavity production by Cornell, cavity treatment and test by KEK.

Basic SRF Cavity Research after 30+years: What's left?

- After overcoming many limitations (normal-conducting inclusions, field emission, …), we finally can <u>study the basic superconducting RF behavior</u> of niobium!
- Two mayor open physics questions in SRF:
  - ⇨ Why does the RF surface resistance increase strongly at high RF fields?
  - ⇨ What is the RF critical magnetic field?
    - ⇨ How and when does flux penetrate at high RF field?

SRF for future Machines around the World

Planed SRF Driven Accelerators

Proton Driver

8 GEV, 336 s.c. cavities

International Linear Collider

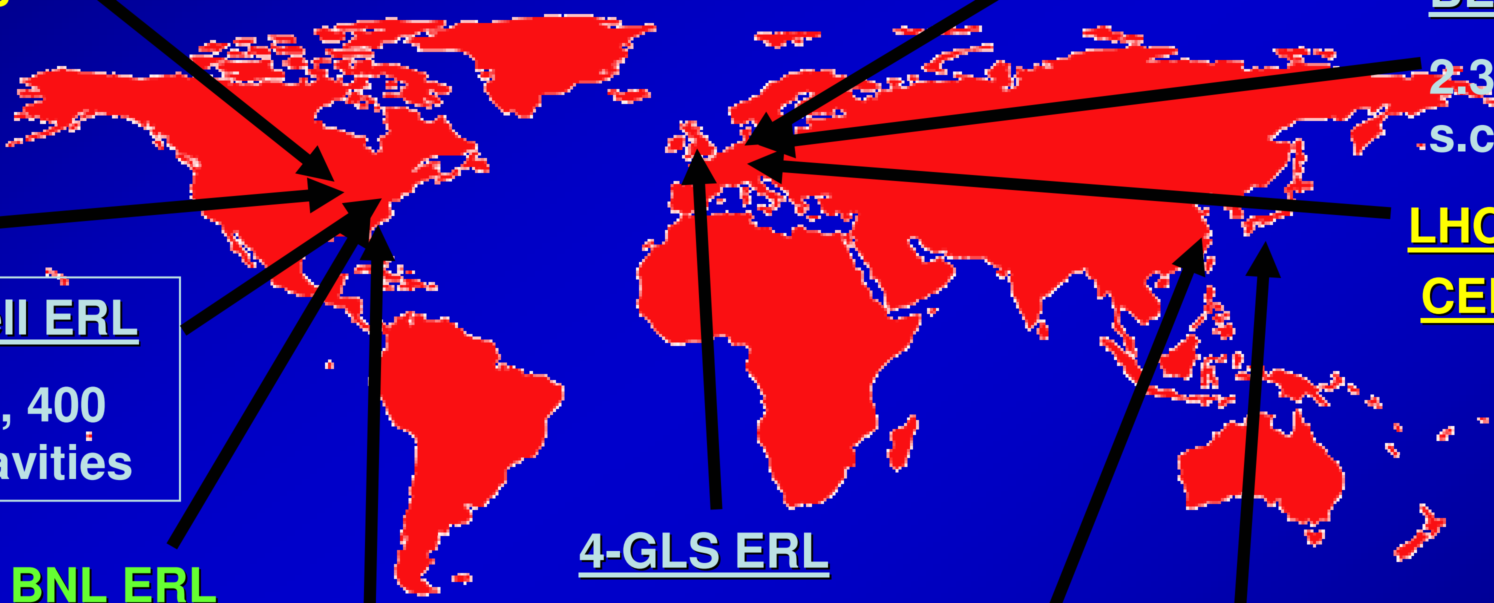
500 GeV, 16000 s.c. cavities

XFEL

20 GEV, 800 s.c. cavities

BESSY FEL

2.3 GEV, 144 s.c. cavities



RIA

LHC, CERN

CERN SPL

Cornell ERL

5 GeV, 400 s.c. cavities

BNL ERL Electron Cooler

CEBAF Upgrade

4-GLS ERL

0.6 GeV, >30 s.c. cavities

KEK ERL Light Source

Shanghai Light Source

SRF at Cornell

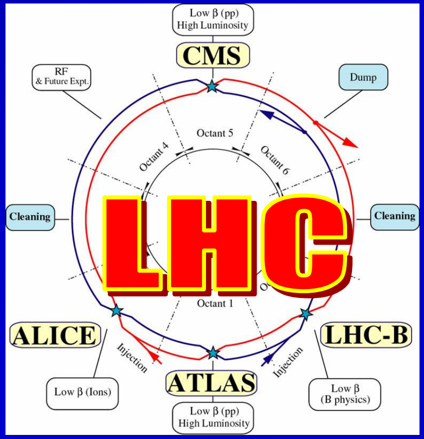
History of SRF for Accelerators (I)
From a nice technology …

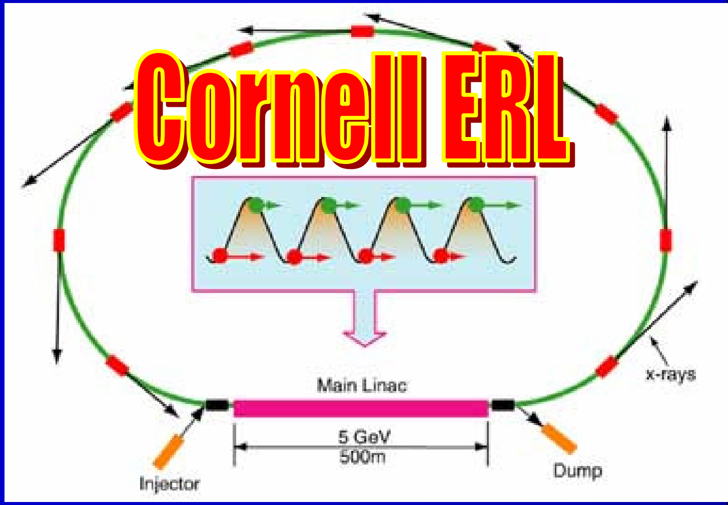
- 1965, Stanford U.: R&D on superconducting cavities starts
- 1968, Cornell: R&D on superconducting cavities starts
- 1975, Cornell Electron Synchrotron: First SRF cavity in a high-energy-physics accelerator
- 1982, CESR: First test of a SRF cavity in a high-energy-physics storage ring.
- 1990, Cornell: First TESLA (International Linear Collider, ILC) workshop
- 1993, Cornell : First ILC multi-cell cavity passes 25 MV/m (TESLA design gradient)

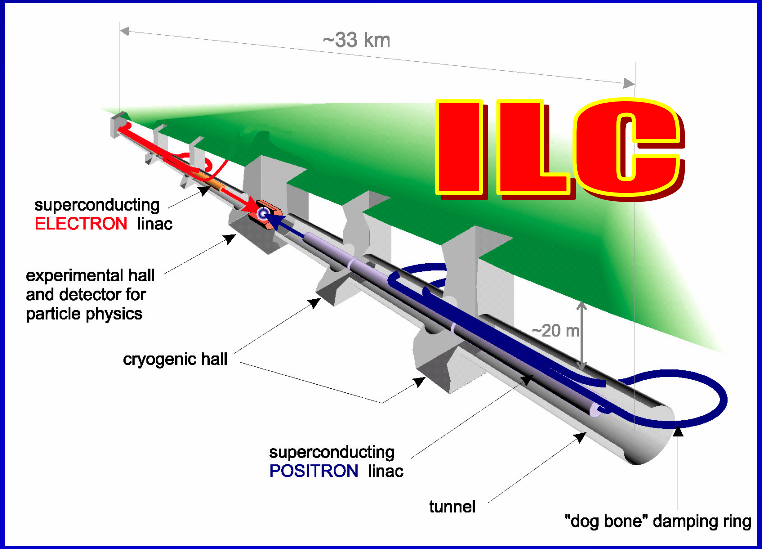
… to the dominating choice of accelerating structure

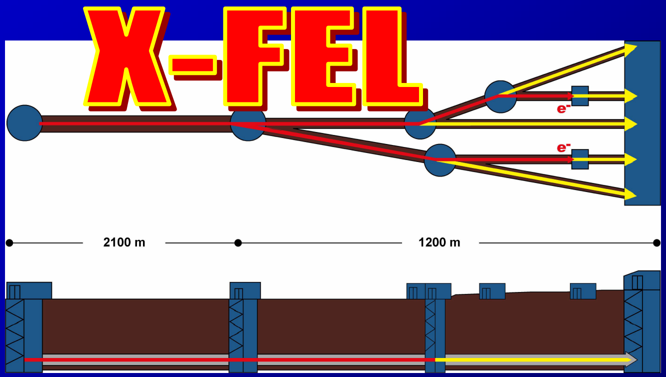
- 1990 to present, Tristan, CESR, HERA, LEP, KEK-B, …: High-energy-physics accelerators use SRF
- 1994, CEBAF: Operation starts with 310 cavities. Cavity design and R&D by Cornell
- 1999, CESR: First storage ring runs entirely on SRF cavities.
- 2000 to present: Storage ring light sources are using the CESR SRF cryostat design (Taiwan, Canada, England, China)
- 2004: International Technology Recommendation Panel recommends cold SRF technology for International Linear Collider (ILC)
- 2005: First cavity passes 50 MV/m (Cavity design and production by Cornell)

Cornell and SRF around the World



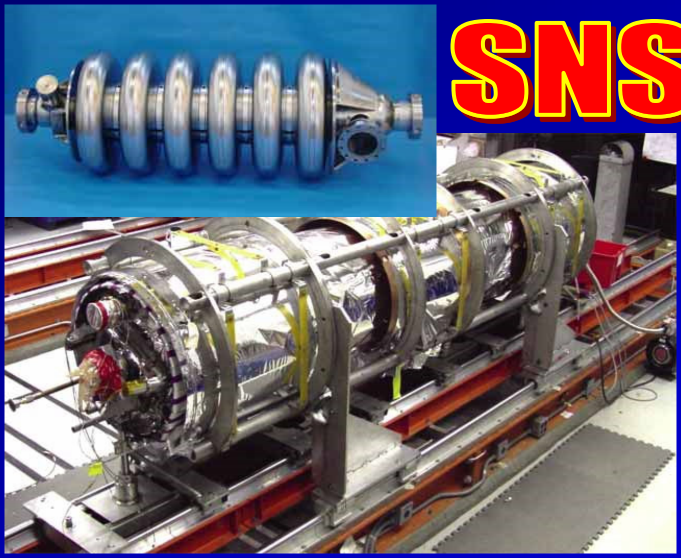




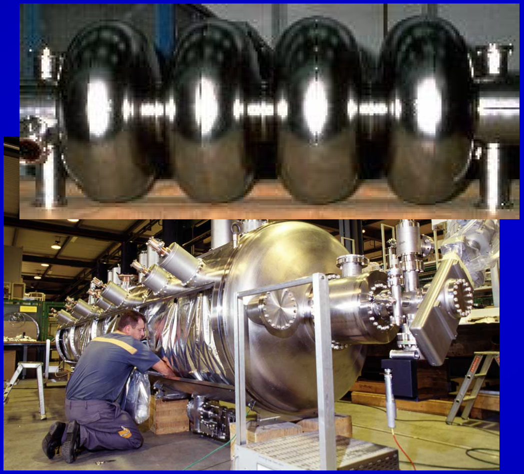


Cornell and SRF around the World

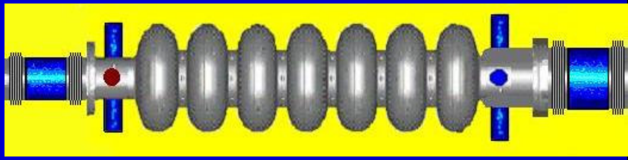
SNS

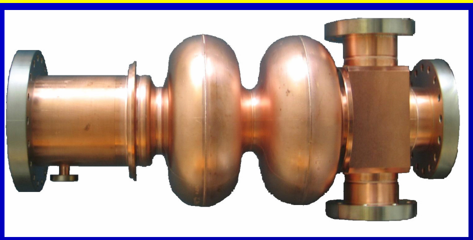


LHC



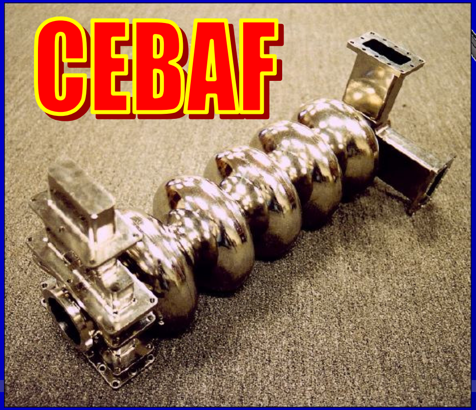
Cornell ERL



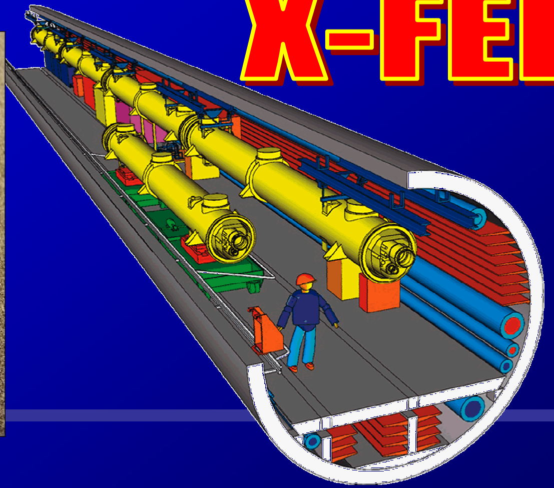


ILC

CEBAF



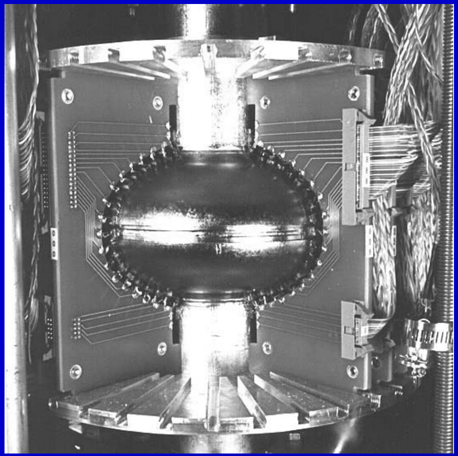
X-FEL



Hot Topics and R&D at Cornell

- Highest gradients in solid niobium cavities
- What is the ***RF*** critical field of superconductors?
- Low cryogenic losses at high fields
  - Surface roughness, density of grain boundaries, pollution at metal-oxide interface?
- Alternative materials for superconducting cavities
  - Nb3Sn, high Tc superconductors,...
- Interaction between cavity and beam
  - Excitation and damping of higher-order-modes, beam focusing, emittance growth, THz radiation, …
- Digital RF field control
- …

From Experimental Work to Theory



Superconductor at T>0, H>0
Nonlinear BCS Theory

$$R_s(\beta) = \frac{\omega^2}{T}\exp\left(-\frac{\Delta}{k_B T}\right)\sum_{n=0}^{\infty} g_n(\beta)\left[A(\omega) + \frac{1}{2n+1}A\left(\frac{\omega}{2n+1}\right)\right],$$

$$g_n = \frac{(2n+1)!!}{2^{n-1}(2n)!(n+2)!(n+1)}\int_0^{\pi}\sin^2 t(\beta_{dc} + \beta_0\cos t)^{2n}\frac{dt}{\pi},$$

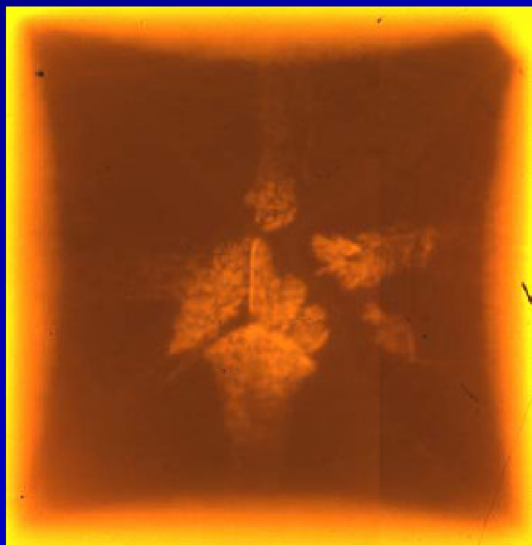
$$R_{bcs} = \omega^2\frac{A(\omega)}{T}\exp\left(-\frac{\Delta}{k_B T}\right), \qquad A \propto \frac{\Delta\mu_0^2 n_0 e^2\lambda^4}{p_F}\ln\frac{k_B T\Delta\xi^2}{\hbar^2\omega^2\lambda^2}$$

Vertex Penetration at Grain Boundaries?

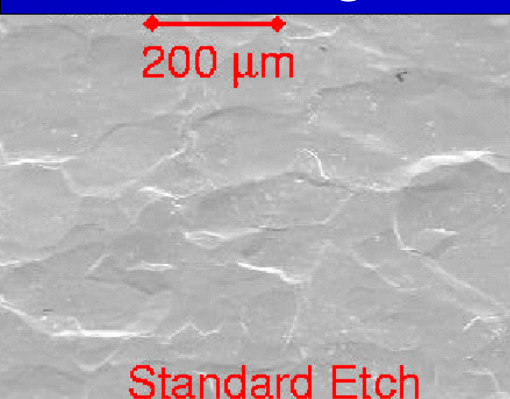
$$\tilde{R}_s(T,H) = R_s(T,H)\left[1 + \frac{g}{1-(H_0/H_{b0})^2}\right] + \frac{R_n(H_0)}{1-(H_0/H_{b0})^2}$$

From Small to Large

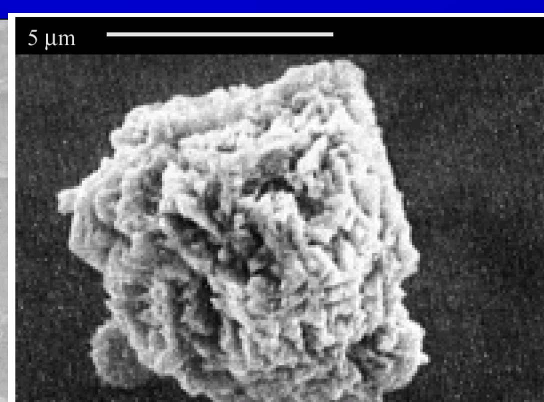
Flux Penetration at Grain Boundaries



Surface Roughness

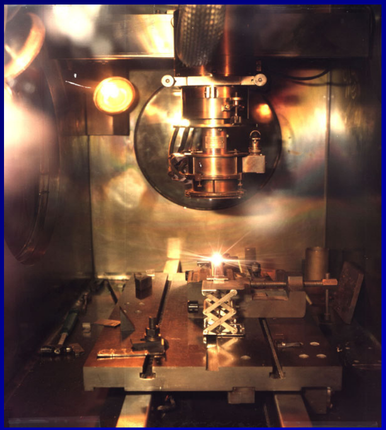


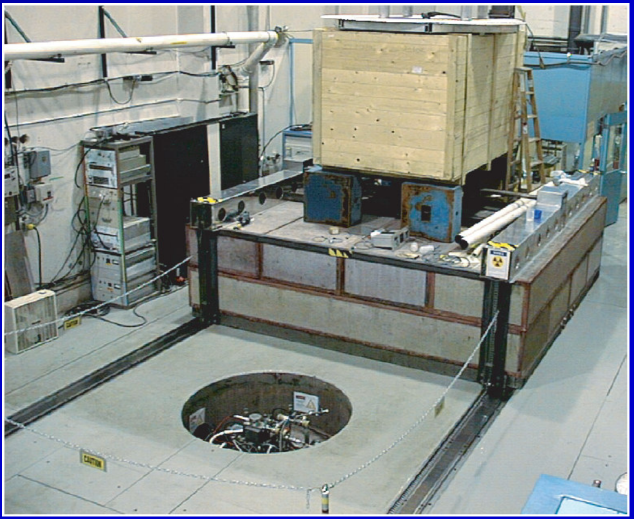
Field Emission

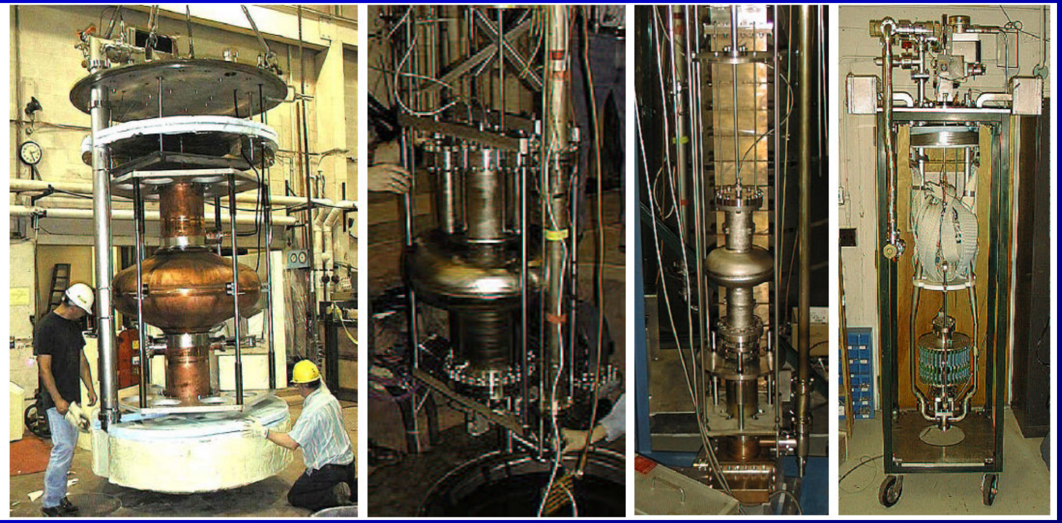


SRF Tour

SRF R&D Work at Cornell: Newman Basement







Basic SRF research, SRF for CESR, Neutrino factory/ μ-Collider, ILC, Cornell ERL, …

Fun in the Newman Basement