Road Map
A view to the future from a look at the past

Padamsee

Four Decades of SRF Success Stories

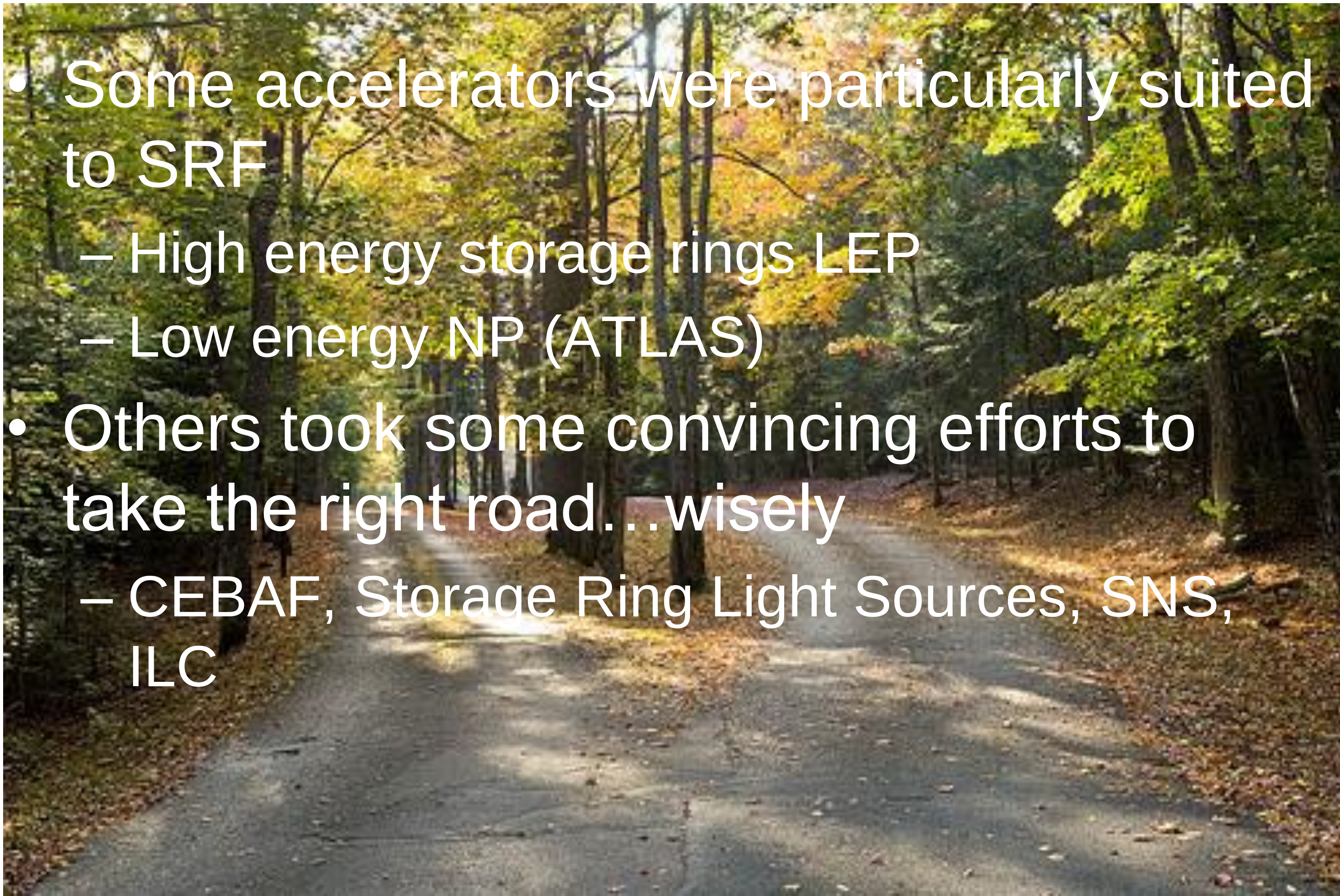
- SRF Started as an exotic technology in the 1960’s
- Really took off in the 1980’s

Now become an enabling technology for many accelerators

Major Impact on Broad Spectrum of Science

- Starting with High Energy Physics and Low Energy Nuclear Physics
  - (TRISTAN, HERA…+ ATLAS...)
- Penetrated Medium Energy Nuclear Physics
  - (CEBAF)
- Storage Ring Light Sources
  - (CHESS, CLS, TLS, DIAMOND..)
- Linac Based Light Source
  - (JLABFEL, TTF-I, FLASH)
- Neutron Source - Proton Source
  - (SNS)

There Were Many Forks in the Road (of course)



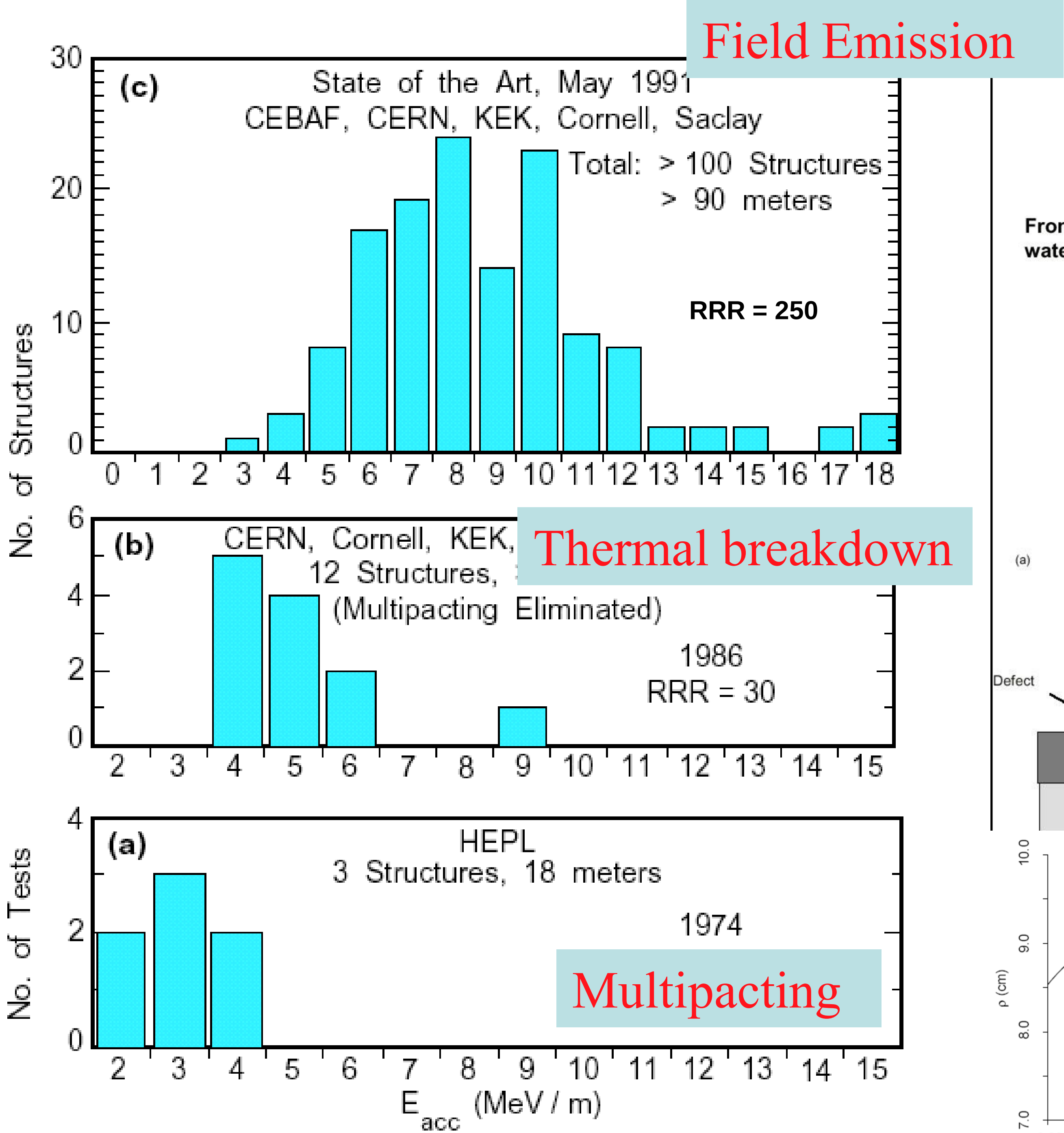
- Some accelerators were particularly suited to SRF
  - High energy storage rings LEP
  - Low energy NP (ATLAS)
- Others took some convincing efforts to take the right road…wisely
  - CEBAF, Storage Ring Light Sources, SNS, ILC

Major Lessons from 4 Decades of SRF Development

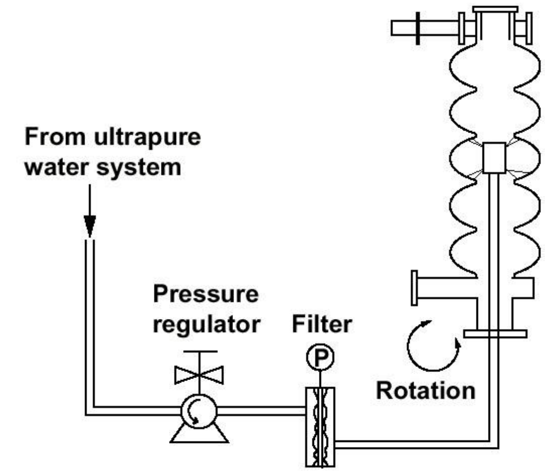
- Lesson 1 : Performance drives application=> Keep pushing performance limits
- Past :
  - 4 – 8 MV/m
    - TRISTAN, HERA, CEBAF, LEP-II, CESR-C, KEK-B, Light Sources (CLS, TLS, DIAMOND…)
  - 10 – 15 MV/m
    - JLAB FEL,TTF-I, SNS
  - 20-25 MV/m
    - FLASH
- Future (Plans Discussed at These Workshops)
  - 15 – 20 MV/m
    - ERL, FEL…
  - 25 MV/m
    - XFEL, PX…
  - 35 MV/m
    - ILC

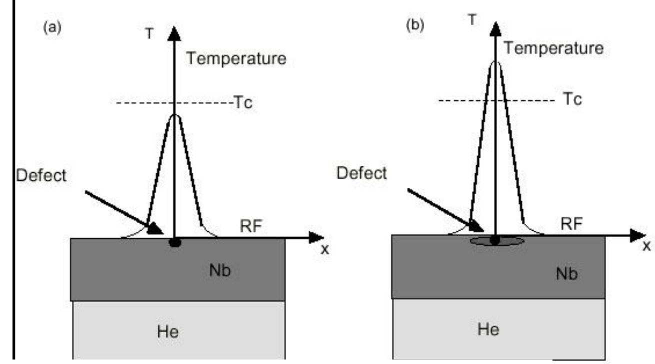
Lesson 2

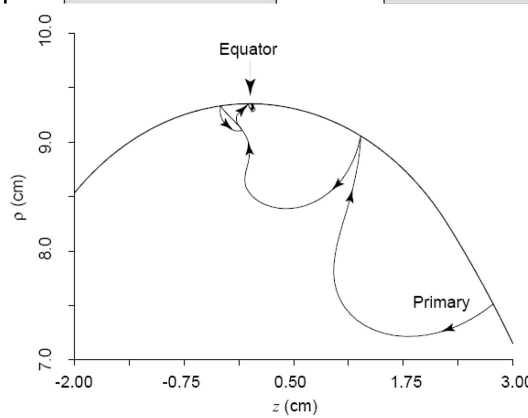
- Understanding (~ Science) drives performance
- Leads to effective solutions
- Multipacting solved: spherical (elliptical) cavity geometry
  - 5 – 8 MV/m
- Thermal breakdown solved: high purity Nb
  - 10 – 15 MV/m
- Field emission solved: high pressure rinsing
  - 15 – 25 MV/m
- Q-slope solved: EP and bake
  - 25 – 35 MV/m
- => Support and Promote science and understanding

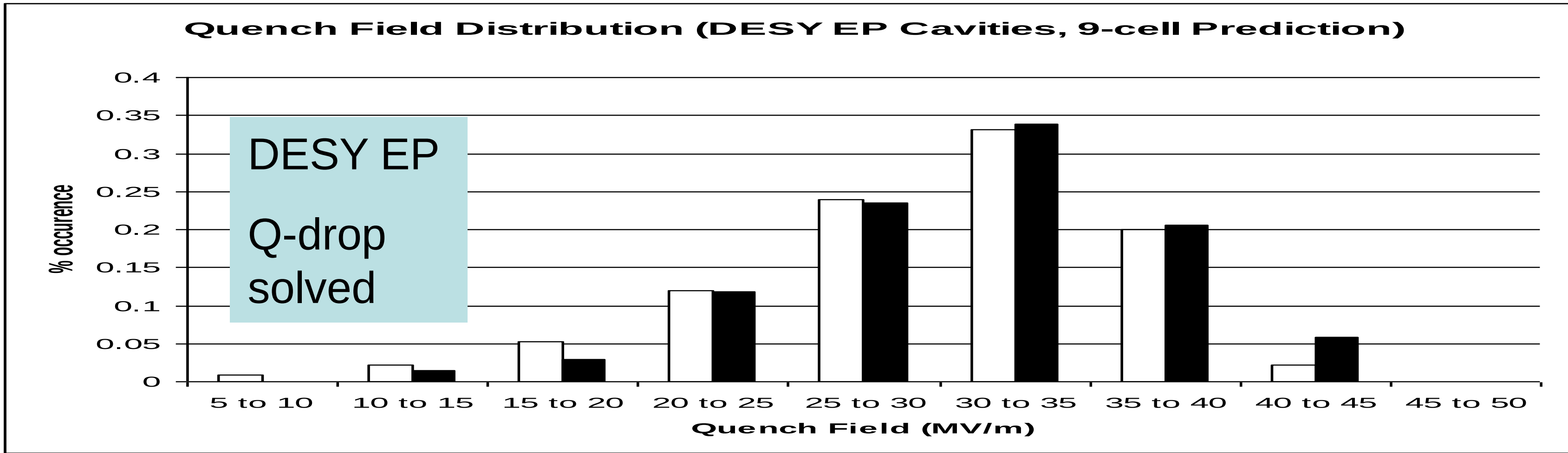

Field Emission
(c)
State of the Art, May 1991
CEBAF, CERN, KEK, Cornell, Saclay
Total: > 100 Structures
> 90 meters
RRR = 250
No. of Structures
Thermal breakdown
(b)
CERN, Cornell, KEK,
12 Structures,
(Multipacting Eliminated)
1986
RRR = 30
(a)
HEPL
3 Structures, 18 meters
1974
Multipacting
No. of Tests
E acc (MeV / m)

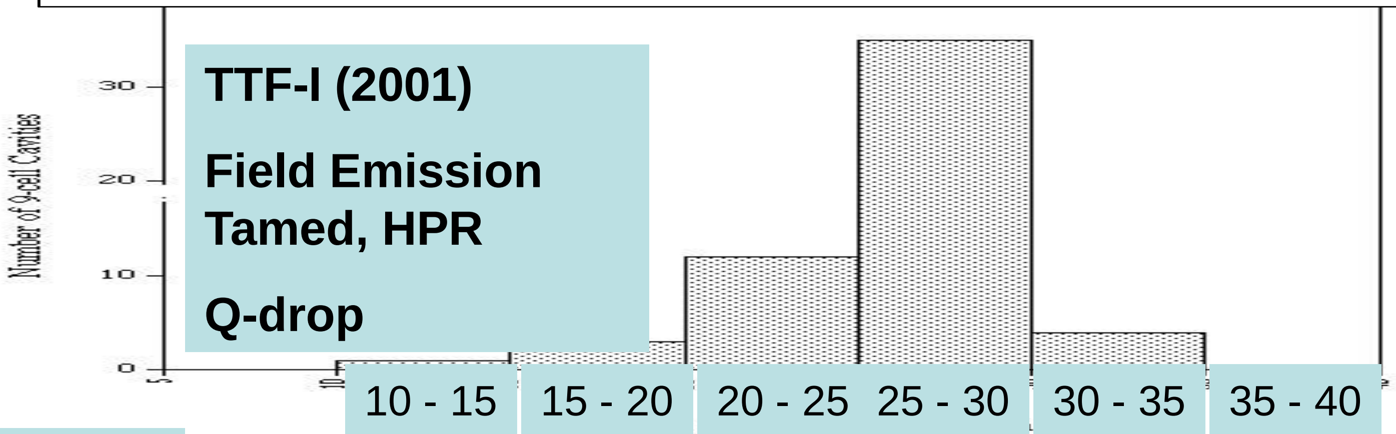
Cures

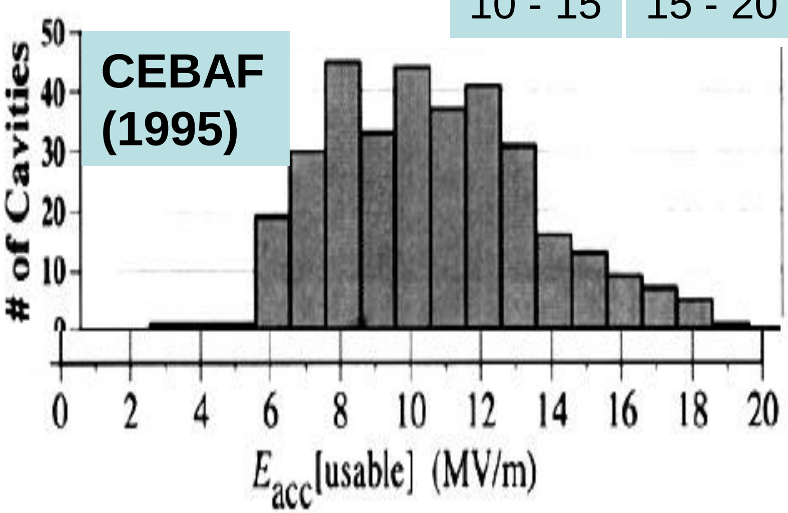

From ultrapure water system
Pressure regulator
Filter
Rotation

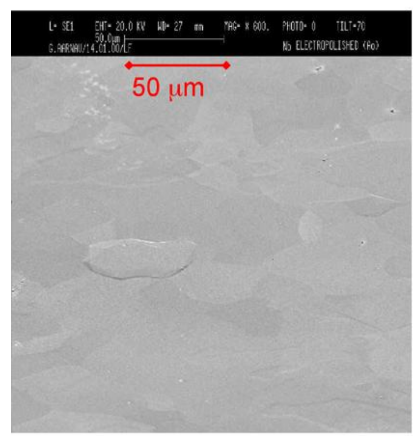

(a)
T
Temperature
Tc
Defect
RF
x
Nb
He
(b)
T
Temperature
Tc
Defect
RF
x
Nb
He

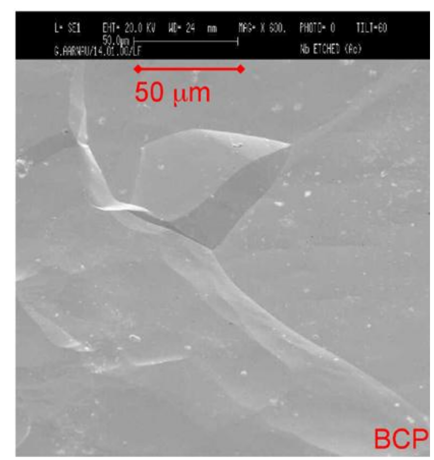

Equator
Primary
ρ (cm)
z (cm)


Quench Field Distribution (DESY EP Cavities, 9-cell Prediction)
% occurence
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
5 to 10
10 to 15
15 to 20
20 to 25
25 to 30
30 to 35
35 to 40
40 to 45
45 to 50
Quench Field (MV/m)
DESY EP
Q-drop solved


TTF-I (2001)
Field Emission Tamed, HPR
Q-drop
Number of 9-cell Cavities
30
20
10
0
10 - 15
15 - 20
20 - 25
25 - 30
30 - 35
35 - 40


CEBAF (1995)
# of Cavities
50
40
30
20
10
0
0
2
4
6
8
10
12
14
16
18
20
E_{acc}[usable] (MV/m)


50 µm


50 µm
BCP

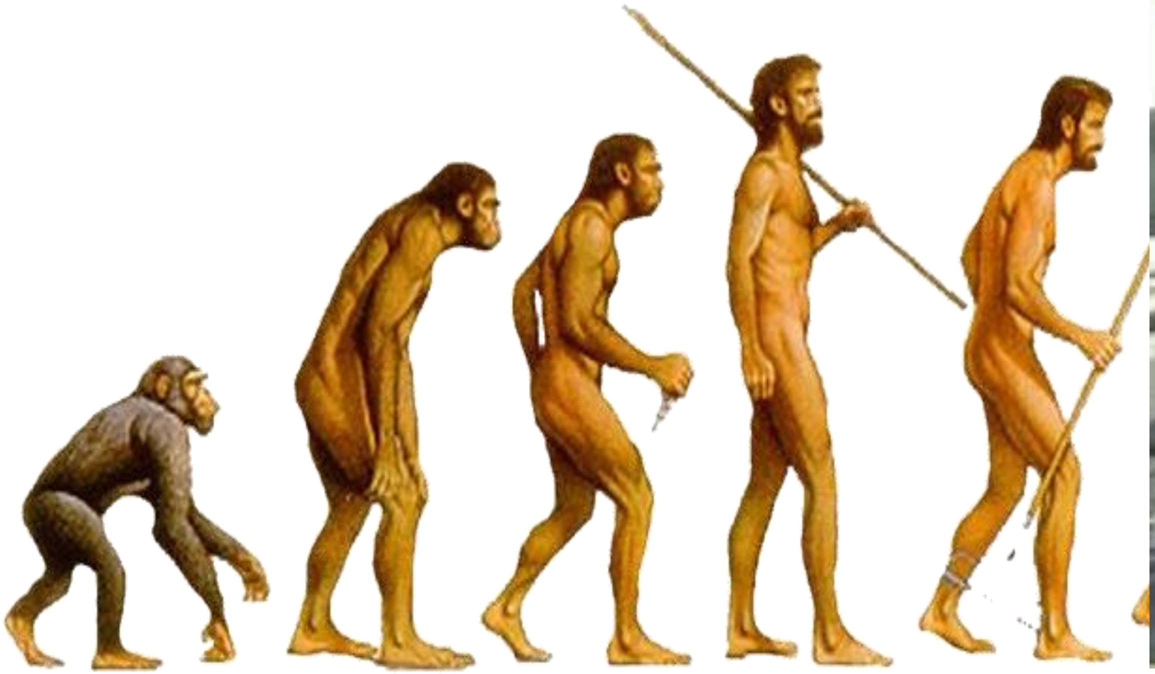
Evolution of Cavity Gradients (1970 – 2009)

And SRF Technology Over 4 Decades

Steady progress in Gradients due to

1) basic understanding of limiting phenomena

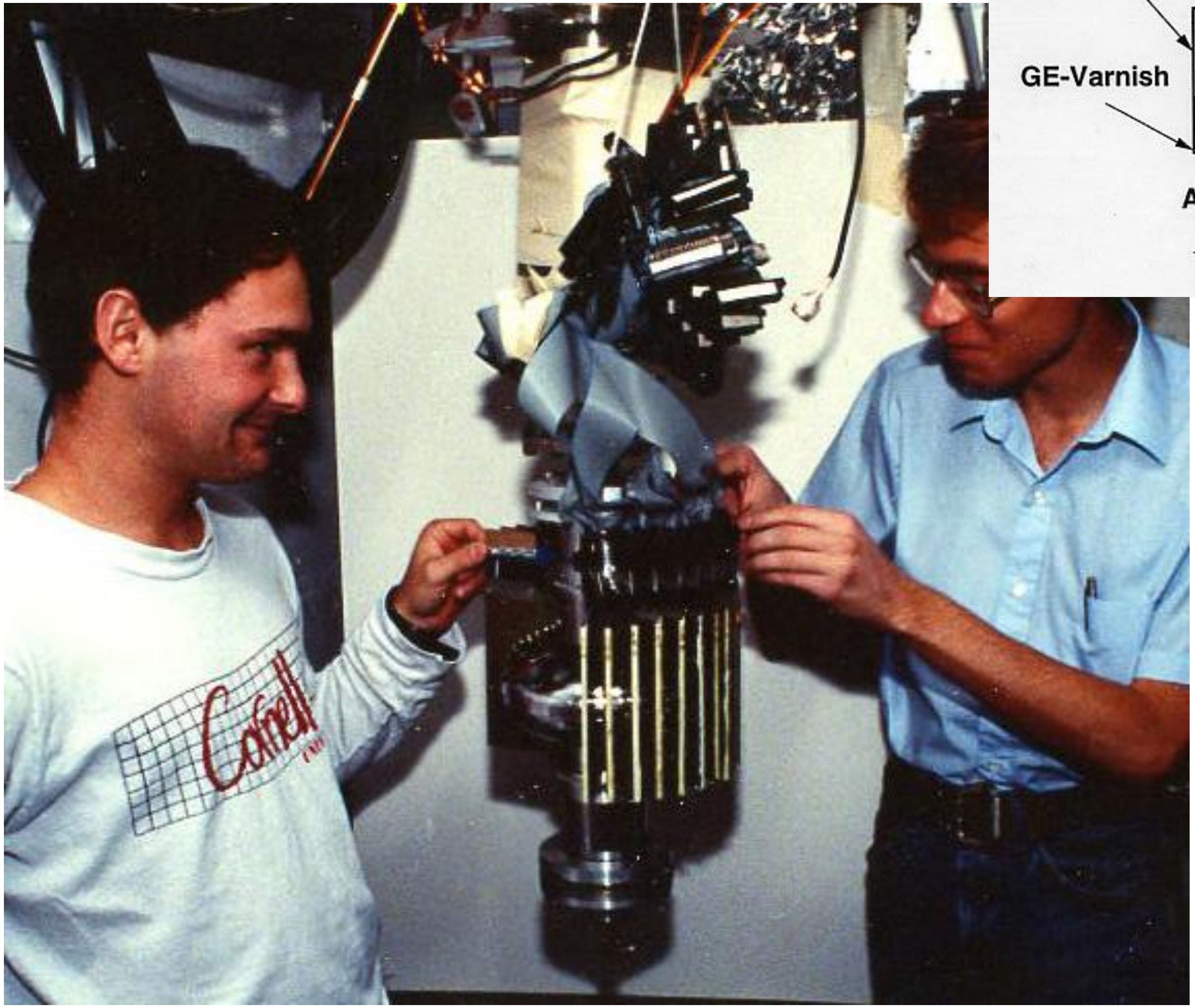
2) and invention of effective cures

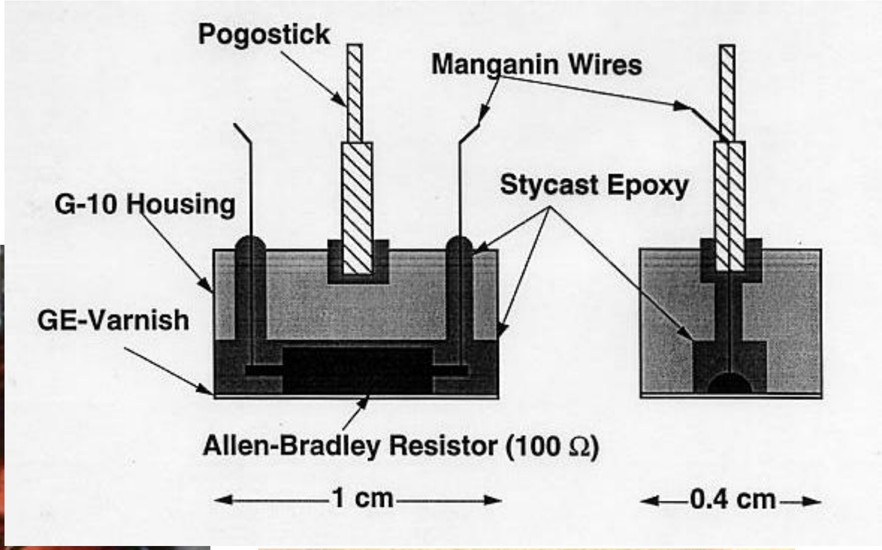


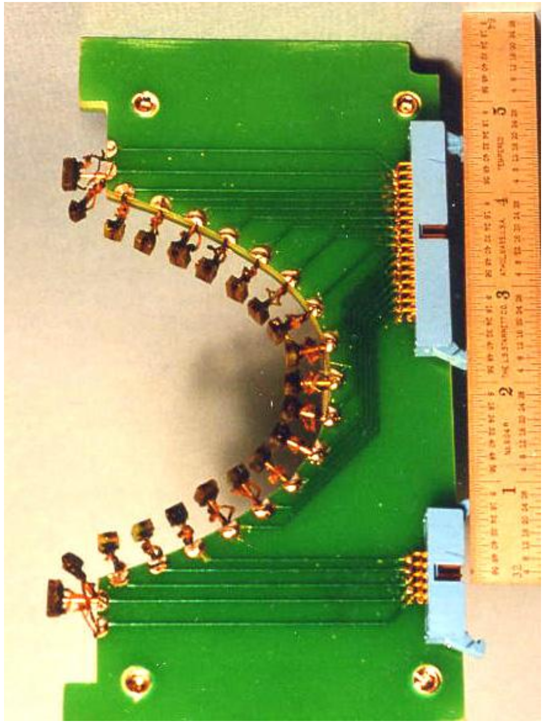
Examples of What Science Taught Us?

- Quench producing defects located with thermometry and characterized with surface analysis
- Field emission sites located with thermometry and characterized
- Mechanism of RF processing understood
- High field Q-slope sites located
  - But not yet fully characterized..

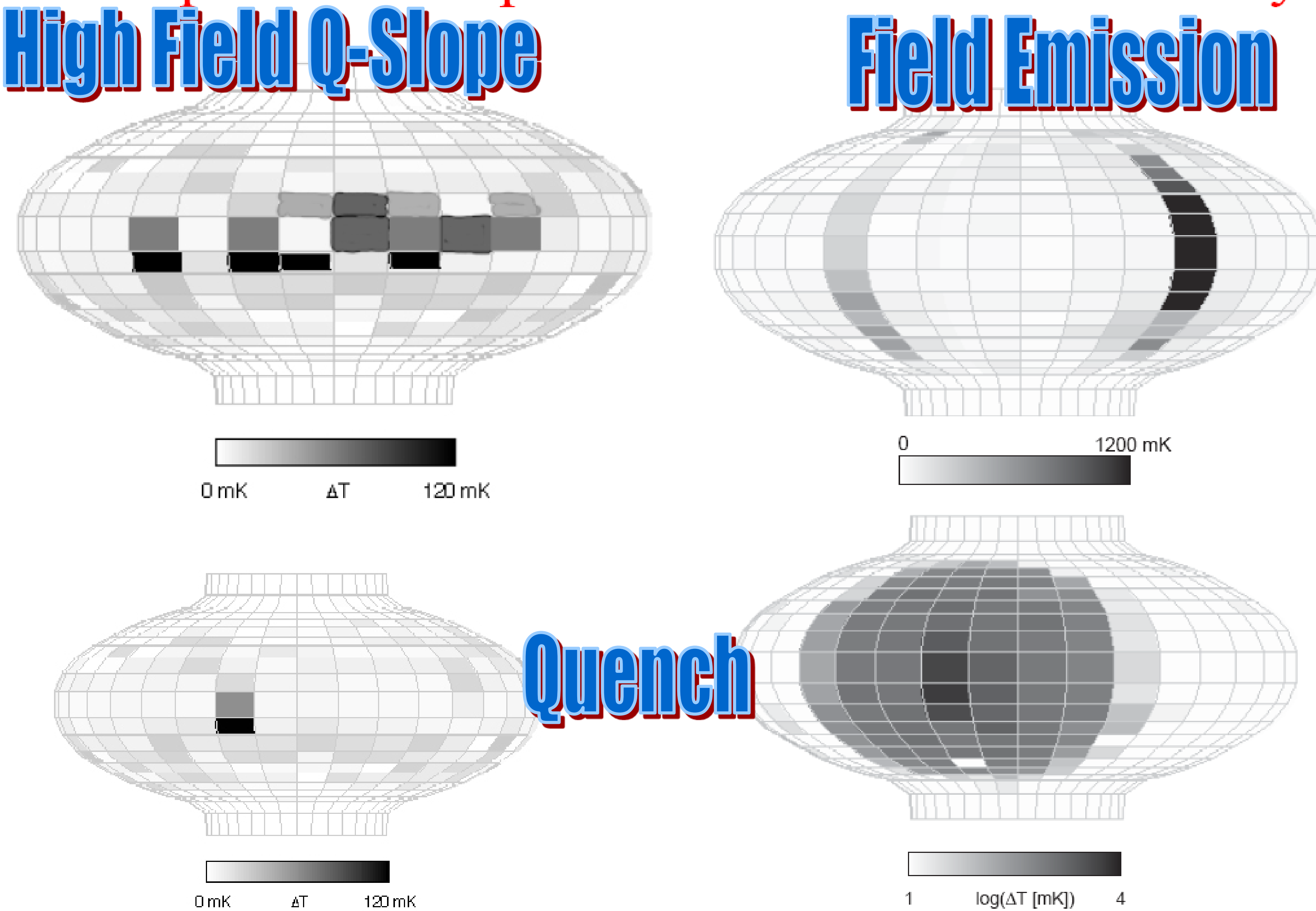
Thermometry System



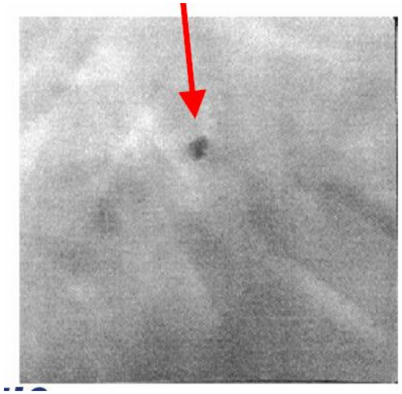




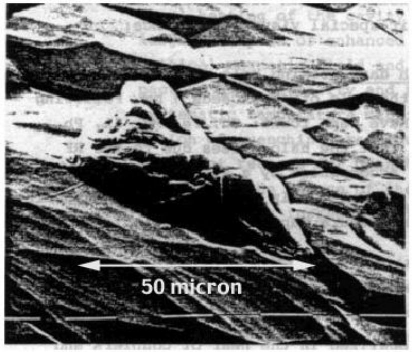
Temperature Maps Reveal Inner Life of Cavity



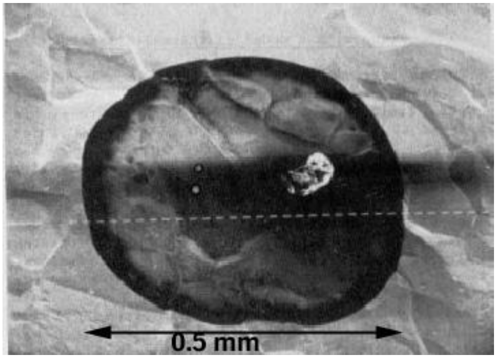
Museum of Defects Causing Quench



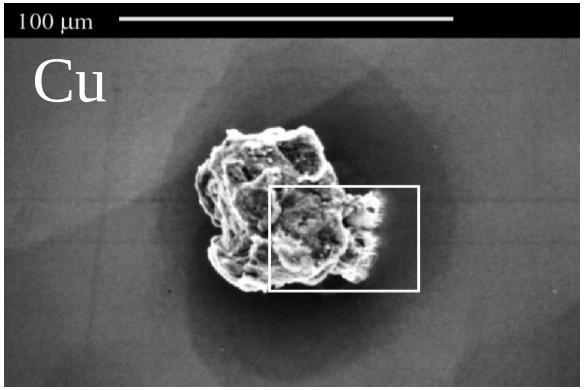
0.2 mm Ta defect, 15 MV/m



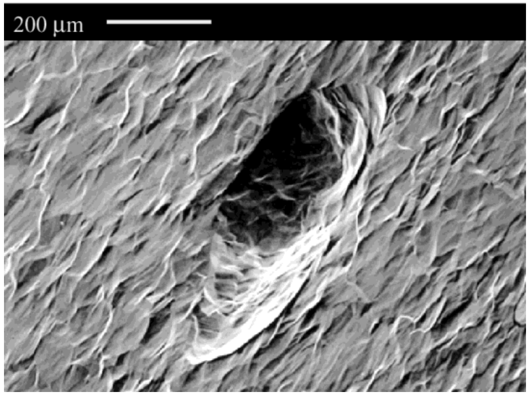
50 μm, with S, Ca, Cl, and K, 11 MV/m



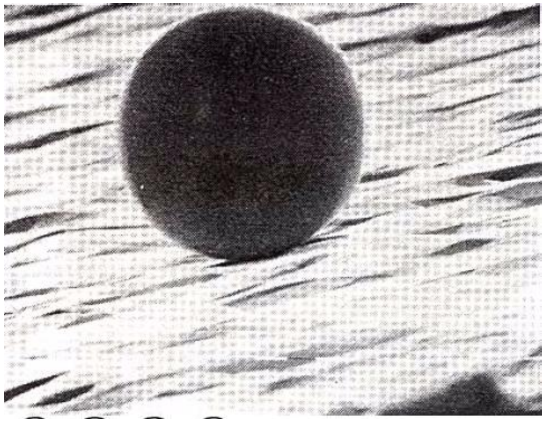
A chemical stain 440 μm in diameter. K, Cl, and P, 3. 4 MV/m



50 micron Cu particle fell into cavity

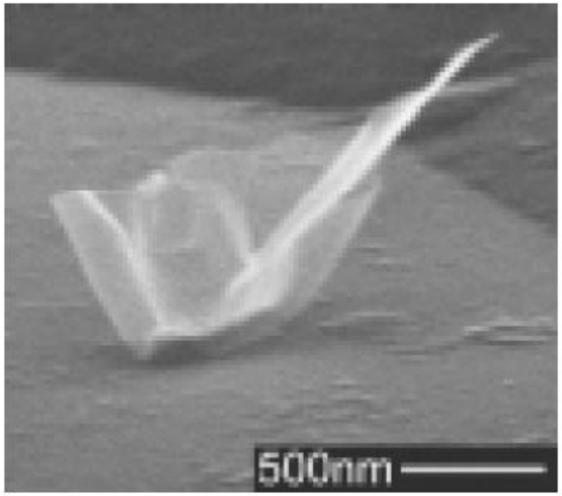


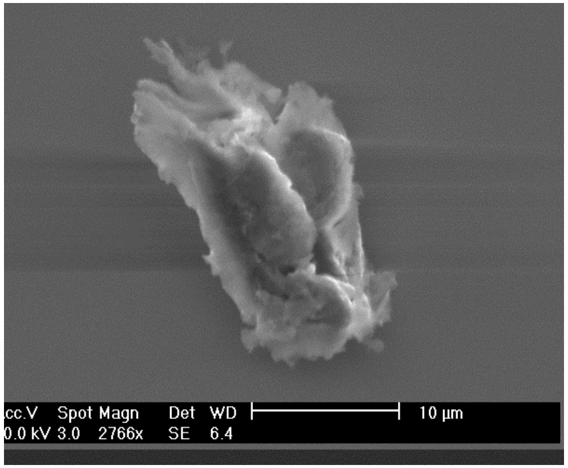
500 x 200 microns pit

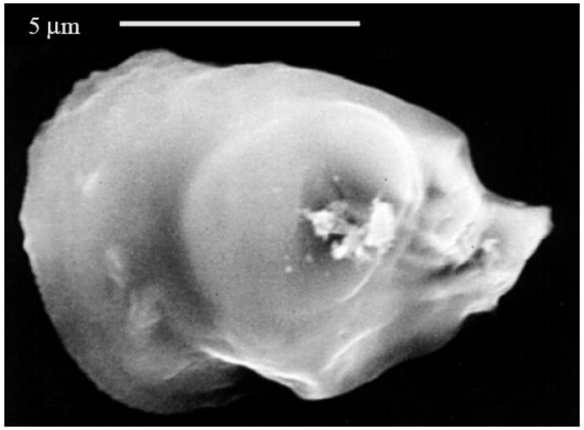


Sub-mm Nb welding ball, avoidable

Museum of Known Field Emitters 0.5 to 10 microns Note the sharp features on the Particles.







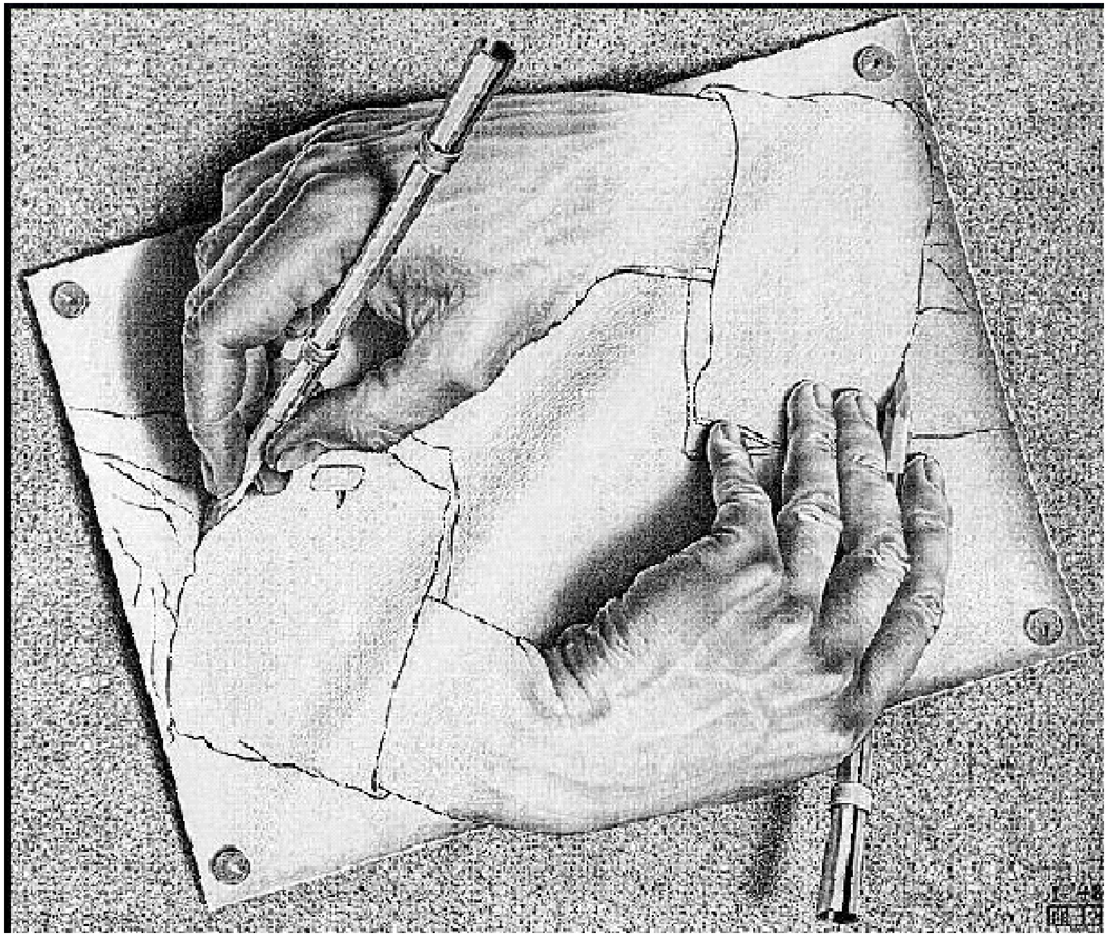
(a) Sub-micron field emitting particles found on sample prepared with 9-cell cavity

(b) Al particle found at a field emission site in the dc field emission scanning apparatus and subsequently analyzed with the SEM

(c) Field emitting particle found with thermometry followed by dissection of a 1.5 GHz cavity. Carbon, oxygen, iron, chromium, and nickel were among the foreign elements detected

Creativity Essential to Design for Cavities and Accessories

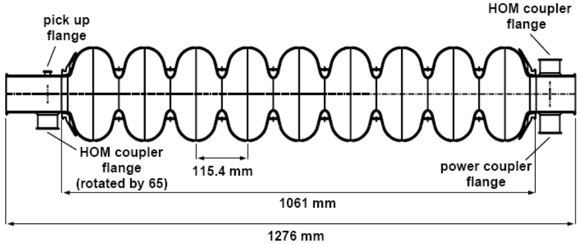
Cavity Design is a Work of Art and Science
Calling for Imagination, Calculation, Symmetry…..



MC Escher

Structure Examples

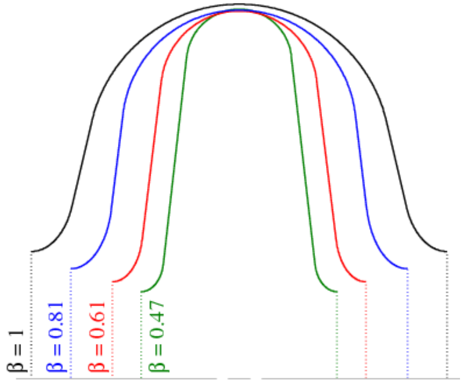
1300 MHz Structures for Accelerating Particles at v ~ c



TESLA-shape

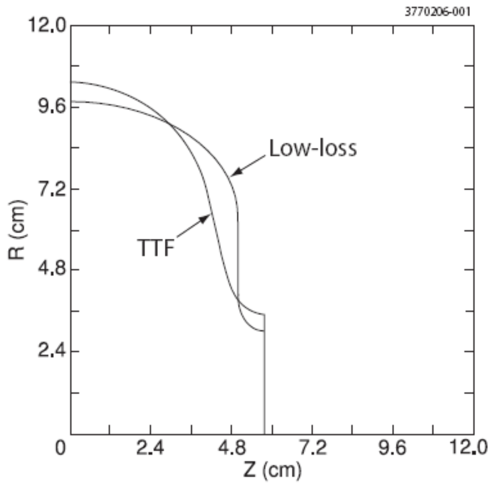
(DESY, TTF)

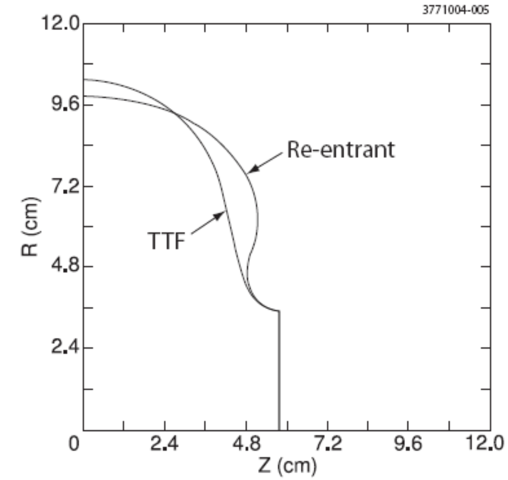
Structures for Particles at v < c (SNS)



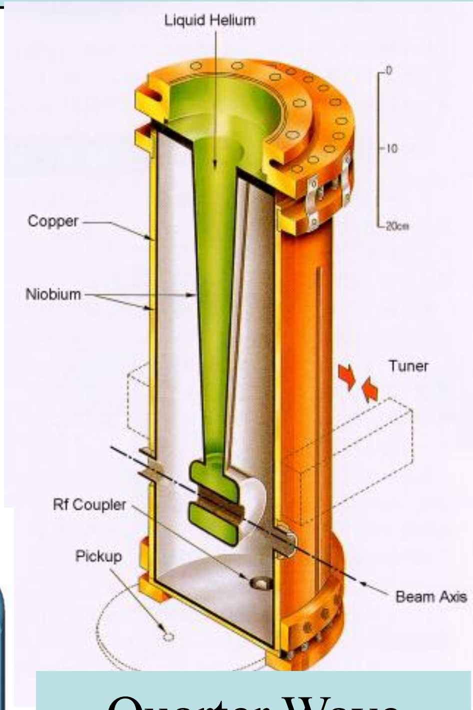
Low-Loss shape (Jlab, KEK…)

Re-entrant shape (Cornell)

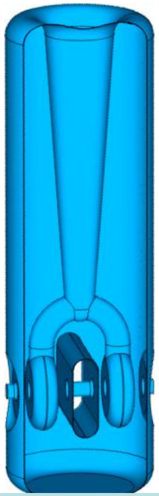




Low Velocity Structures, $\beta = v/c = 0.01 \rightarrow 0.2$

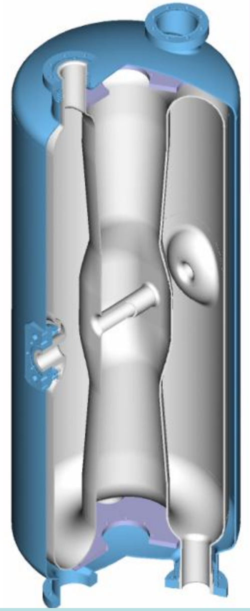


Quarter Wave



Inter-Digital

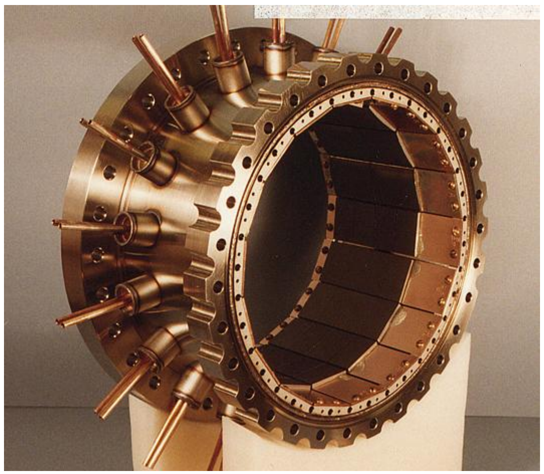
Split -Ring

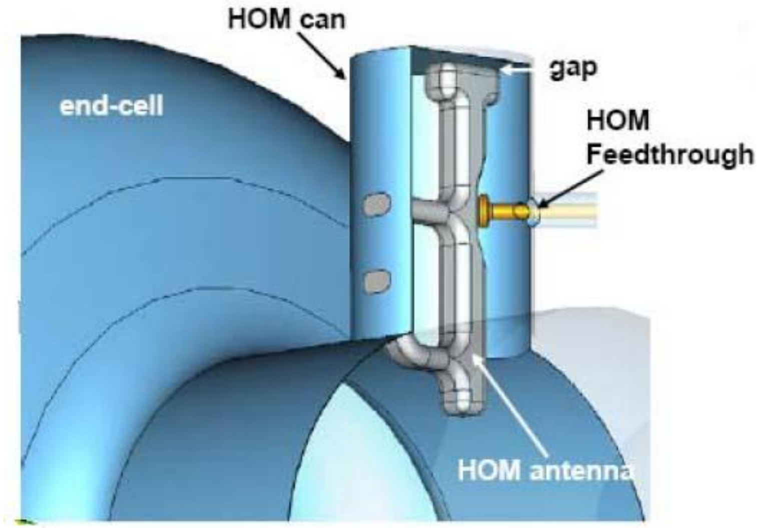


Half-Wave

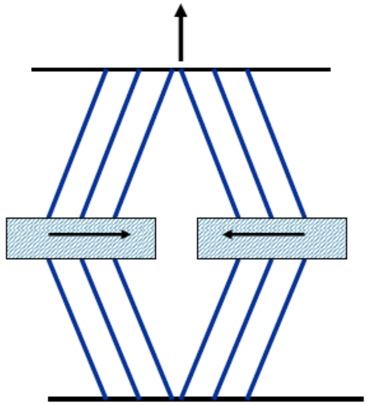
Spoke

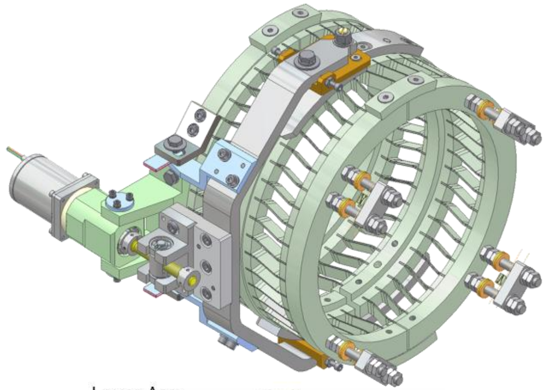
HOM Couplers and Dampers

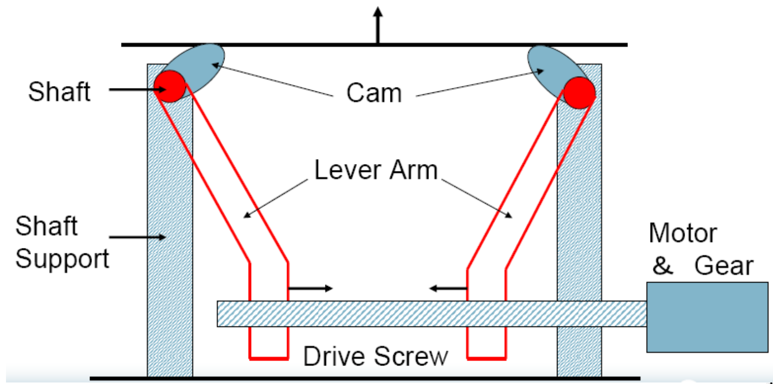


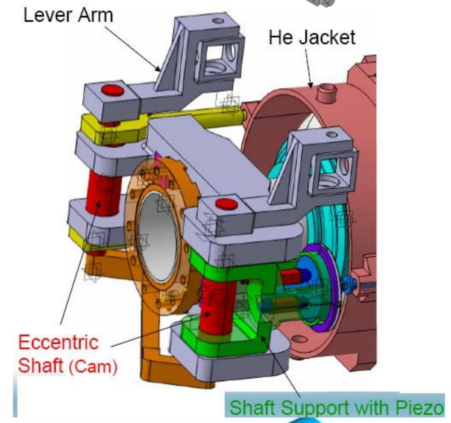


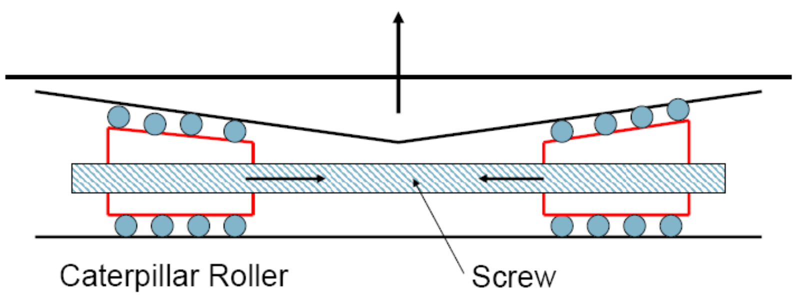
Tuners

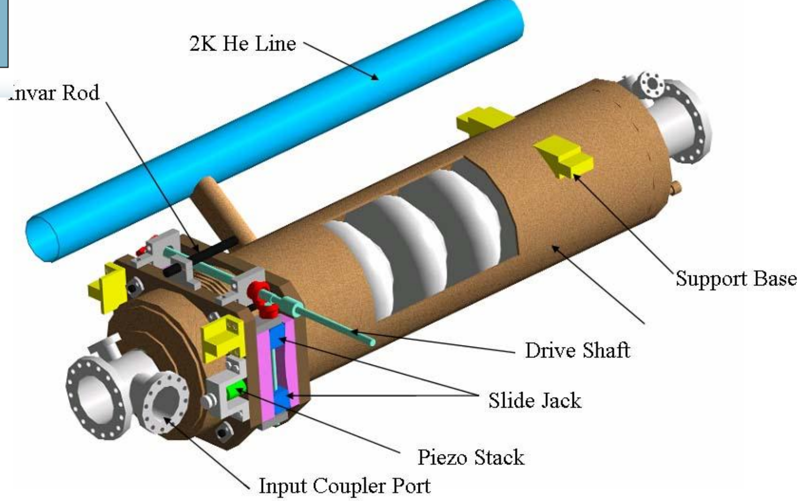




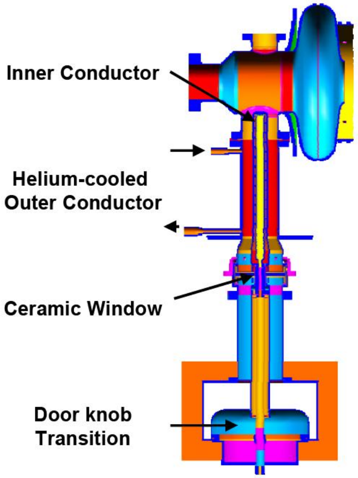

Shaft
Cam
Lever Arm
Shaft Support
Motor & Gear
Drive Screw

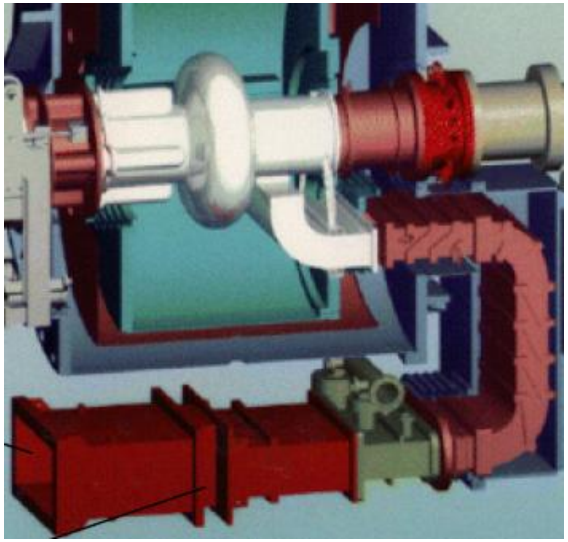

Lever Arm
He Jacket
Eccentric Shaft (Cam)
Shaft Support with Piezo

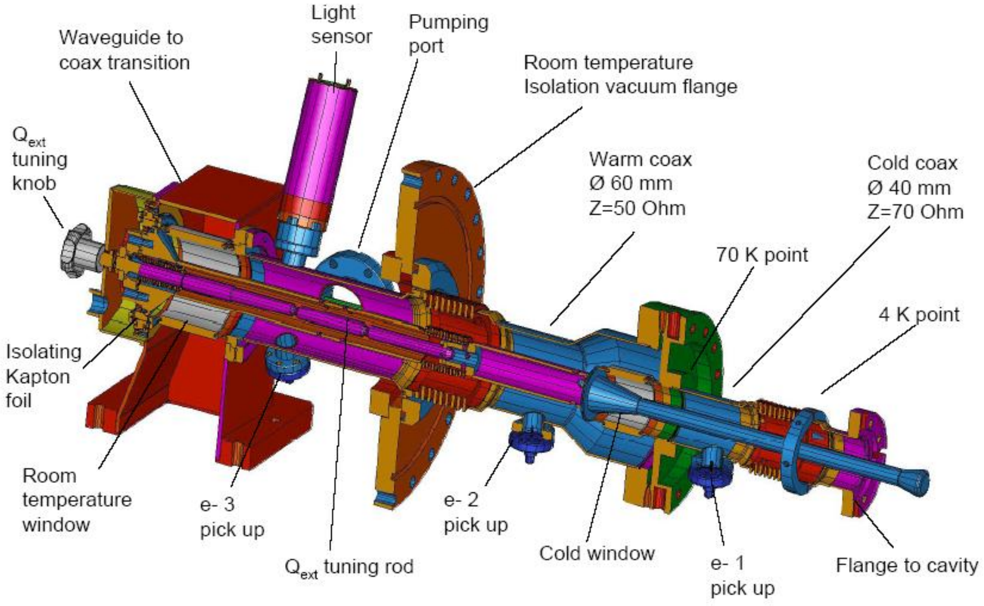

Caterpillar Roller
Screw


2K He Line
nvar Rod
Support Base
Drive Shaft
Slide Jack
Piezo Stack
Input Coupler Port

Input Couplers







Collaboration : Success Examples

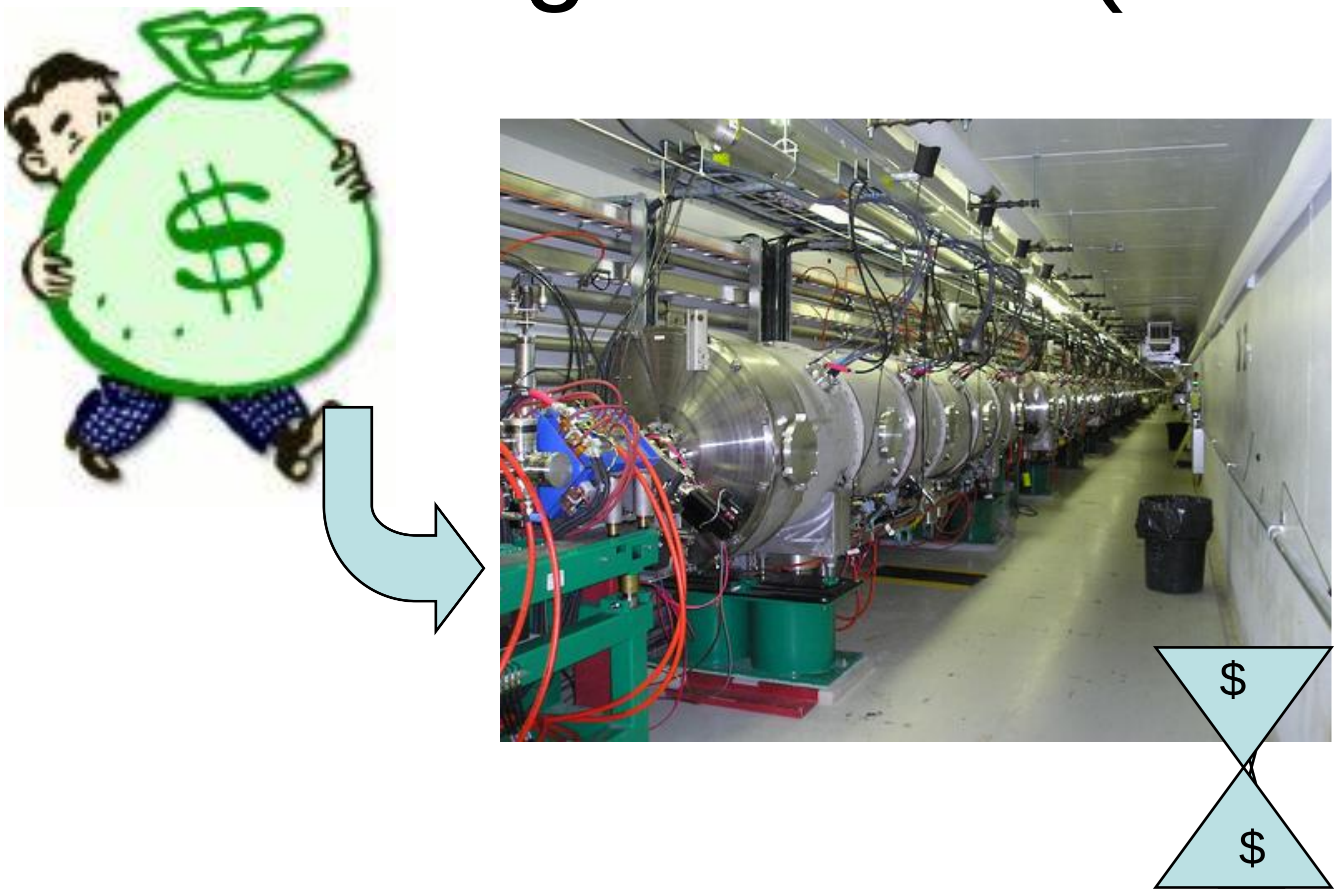
- E.g. Solution of serious H problem, High field Q-drop
  - H: Baking at 600 – 800 C
  - Q-drop: EP and 120 C bake
    - (still waiting for complete understanding)
- The Collaboration Process
  - Theoretical Explanations, Models
  - Co-ordinated cavity tests at various labs
  - Dedicated meetings for discussion of results
  - Ideas for further testing
  - Analytical sample measurements
  - Co-ordinated evaluation of suggested cures
- SRF workshop meets 2 years – not useful/conference
- TTC meetings had the appropriate flavor
  - But now transforming to conference like meetings reporting on project progress
  - Rather than focused discussions to solve a few particular problems

Road Map

Review/Roadmap

- Science/understanding has played a major role in guiding SRF technology development
- Creativity has been essential
  - can lead to many viable options
- Many collaboration success stories
- As this workshop shows, there is an impressive number of on-going projects
  - XFEL 20 GeV, JLAB-upgrade, SNS-uprade, SPIRAL, FRIB..
- And many plans for new projects all around the world…Friday sessions
  - ERL, e-RHIC
  - ESS (like SNS)
  - PX, SPL and High Current Proton Accelerator, EURISOL,
  - ILC
- It will be important to remain in close contact with each other
- On-going projects will need to keep the science and development at healthy levels to ensure project success

Funding Model A (~ Present)



- Strong link between R&D and application

Ideal ? Funding Model

Projects

Science

Assumed Link

Need a Godfather

And Consilieri

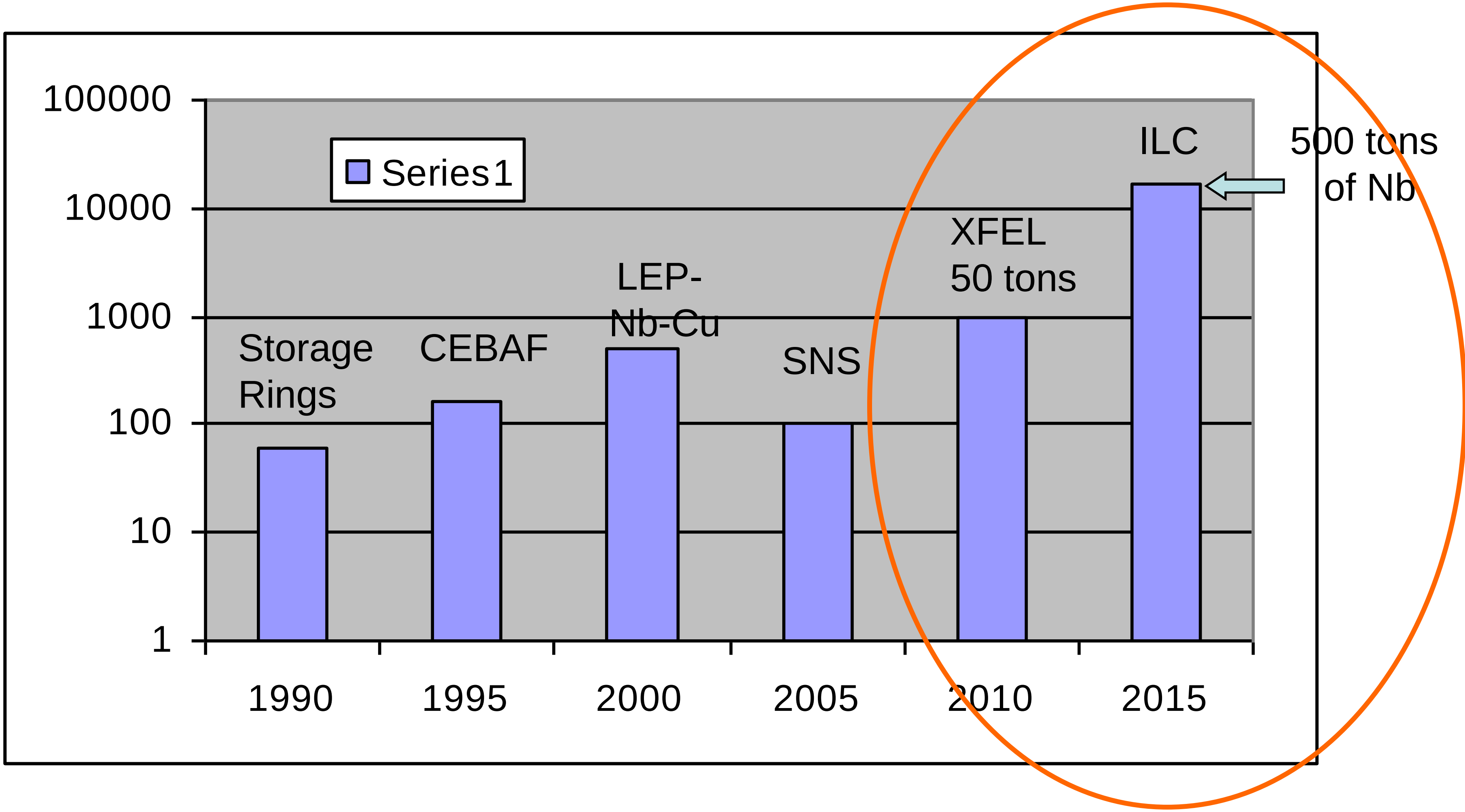
Special Considerations for Wide Open Frontiers and Their Challenges

- ILC
- New Materials (G > 50 MV/m)

ILC Challenges

- Low Yield, large spread
  - Gradient reproducibility (process control)
  - Cavity fabrication success rate
  - Field emission, quench…
- Cost reduction
  - Hydroforming/spinning/Nb-Cu
  - Couplers, tuners…
  - Industrialization
- Large Scale production (see for e.g slide for Nb)
- Good quality control
  - For materials, infrastructure, preparation, assembly
  - consistency
- Political challenges
  - Have to be ready for any scenario by 2012 (LHC results)
  - 250 GeV – 500 GeV
- Parallel projects Pros: synergy, Cons:resource competition
  - XFEL, PX, ERL

Meters of SRF Cavities



Higher Gradient (>35 MV/m) Efforts

- First proposed as “Alternate Design Configuration”
- There is a large phase space of “good ideas”
  - Cavity shapes
  - Large grain
  - Single crystal
- Now mainly for ILC Tev Upgrade?

How Does Past Experience Help to Navigate in Uncharted Waters of ILC-Scale Project

- Benefit from experience of large projects
  - XFEL, XFEL, XFEL
    - Cavities, treatment, couplers, cryomodules, production
- How much is ILC learning from LHC?
- Learn from related communities
  - Clean room/clean water/semiconductor industry
  - Chemistry..e.g. Henkel
  - Metallurgy (e.g experts from MSU now on board)
- Caution : experts tend to suggest tangential paths

Possible Dangerous Waters for ILC

Decreasing ILC- SRF community interaction

- Need more discussion of ideas/science/options/pros and cons
- Within a community wider than ILC Task Forces
  - Like examples given for H-disease, Q-drop
- Task Forces could still co-organize the focused collaboration meetings.
- E.g. Need a more intense/wider co-ordinated effort on
  - Improving gradient yield (process and production)
  - understanding and eliminating weld related pits
  - Infrastructure problems
  - -----

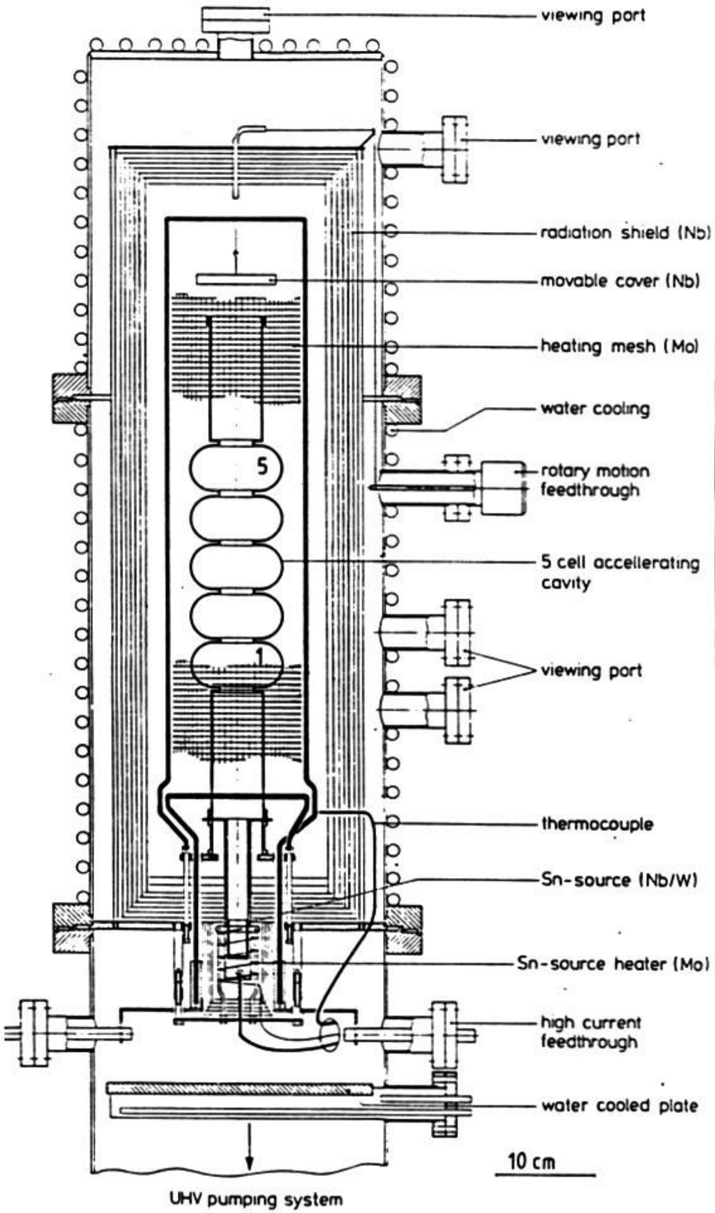
Paths to G > 50 MV/m

- Multilayers: Nb/Nb3Sn
- Nb3Sn, NbN
- MgB2

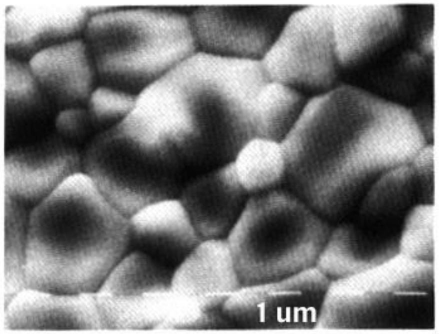
Theory gives hope for 100 – 200 MV/m !

- Until now only GL theory Hsh = 0.75 Hc
- New: Eilenberger (BCS) Theory predicts
- $\boldsymbol{E_{acc}}$ ~ 120 MV/m for perfect Nb_3Sn
- and 200 MV/m for perfect MgB_2 !!
- Strong motivation for materials and cavity push
- But be prepared for a long road to realization
- Can we do it?
- Need Many years of well supported R&D !

Best CW Result Nb_3Sn Fabrication at Wuppertal University



Reaction Furnace



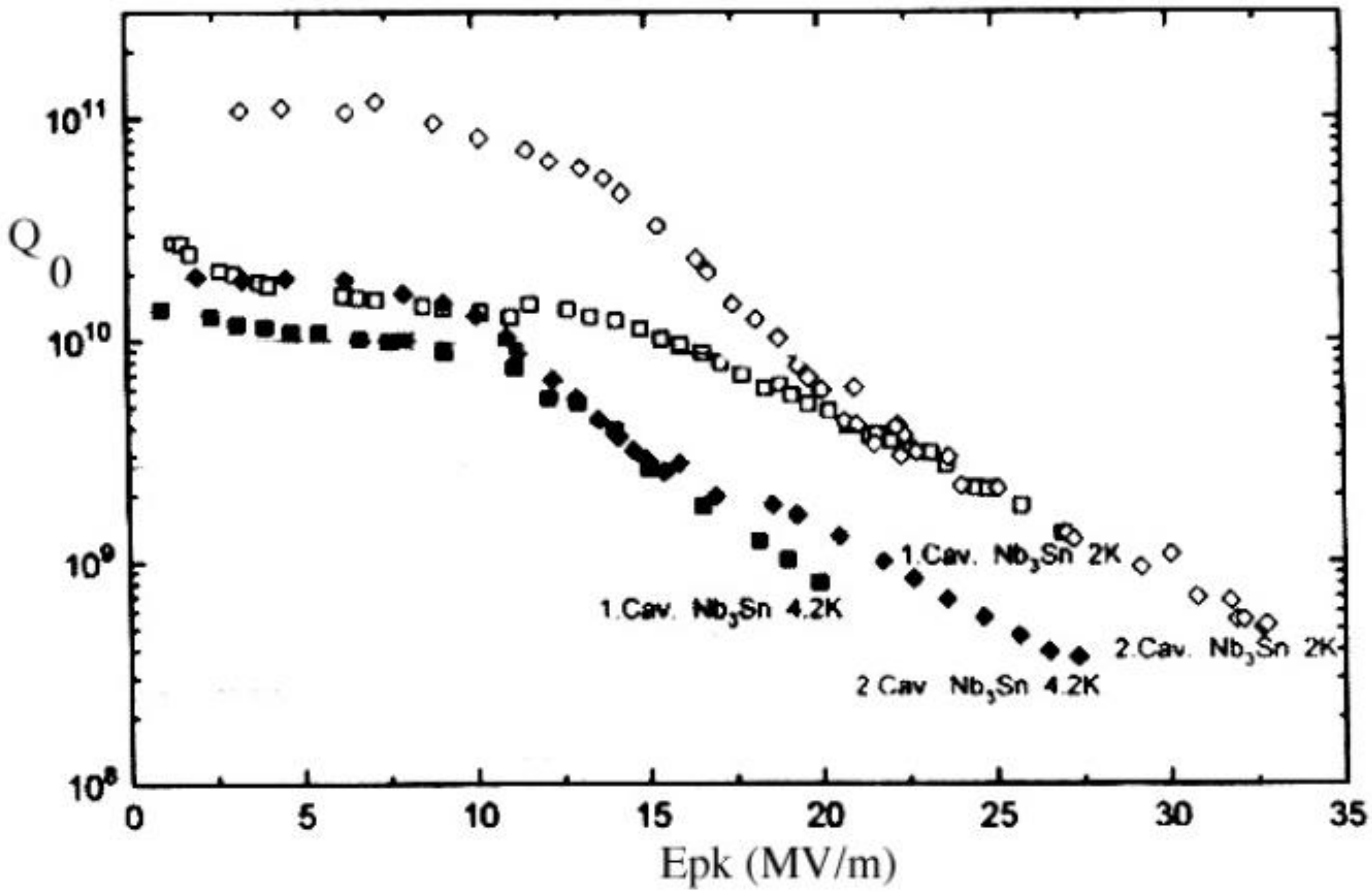
Grain Structure

Start with Nb Cavity, Tc = 9.2K

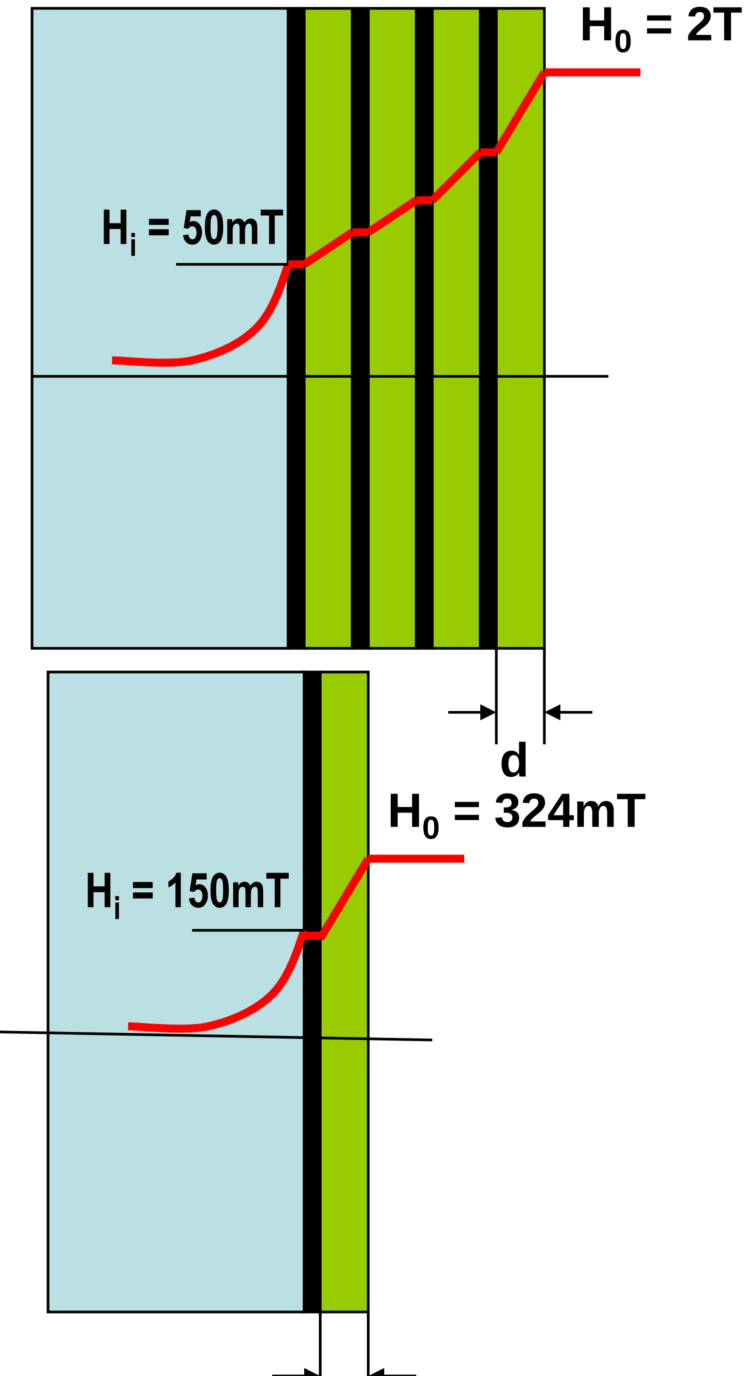
Expose to Sn Vapor

Grow Nb_3Sn by solid state diffusion

Tc = 18 K..achieved!



10^{11}
10^{10}
10^{9}
10^{8}
Q_0
0
5
10
15
20
25
30
35
Epk (MV/m)
1.Cav. Nb_3Sn 2K
1.Cav. Nb_3Sn 4.2K
2.Cav. Nb_3Sn 2K
2.Cav. Nb_3Sn 4.2K



Example: Nb_3Sn layers with d = 30nm
λ_0 = 65 nm and H_{c1} = 2.4T

Peak rf field H_0 = 2T < H_{crit}

Internal rf field H_i = 50 mT (high-Q regime)

A Nb cavity coated by a single Nb_3Sn layer of thickness d = 50nm and an insulator layer in between

If the Nb cavity can withstand H_i = 150mT, then the external field can be as high as

$$H_0 = H_i \exp(d/\lambda_0) = 150 \exp(50/65) = 323.7mT$$

Parting Remarks

- SRF community has a healthy growth due to expanding interest world wide
  - From 80 at Karsruhue to >280 at Berlin
  - Unification of low beta and high beta communities
- SRF community has been a “Family” with much cameraderie
  - To benefit from each other
  - In particular the “Topical Review” aspects of these meetings has been important
  - Example: talks on Tuesday

- Many related workshops
  - TTC, Materials, couplers.
  - Need to work on inter-relationships between these meetings and specific project needs
- Need exciting projects and fundamental research challenges
- to continue to attract more talent..young researchers

Conclusion :General Vision for the Future of SRF