State-of-the-Art and Future Prospects in RF Superconductivity

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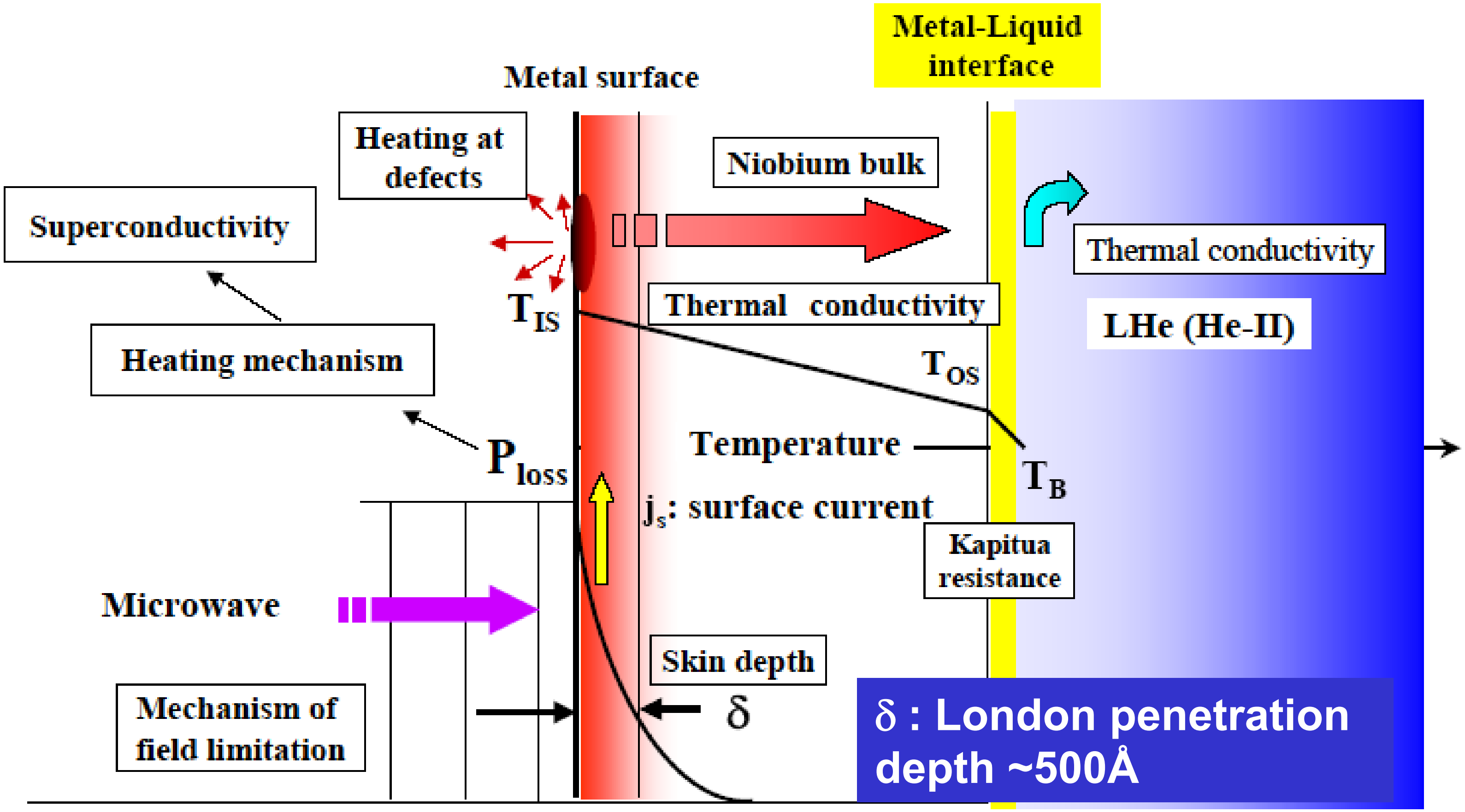
- **Specifics and Constrains in SRF Cavities**
- **SRF Performance on Niobium Cavities Over The Past 50 Years**
- **Future Prospects**

* Moving from KEK to MS, FRIB

SRF Specifics and Constrains



Surface resistance is very small and very small intrinsic surface heating.

➡ *Unexpected phenomenon dominates the heating and limits the performance.*

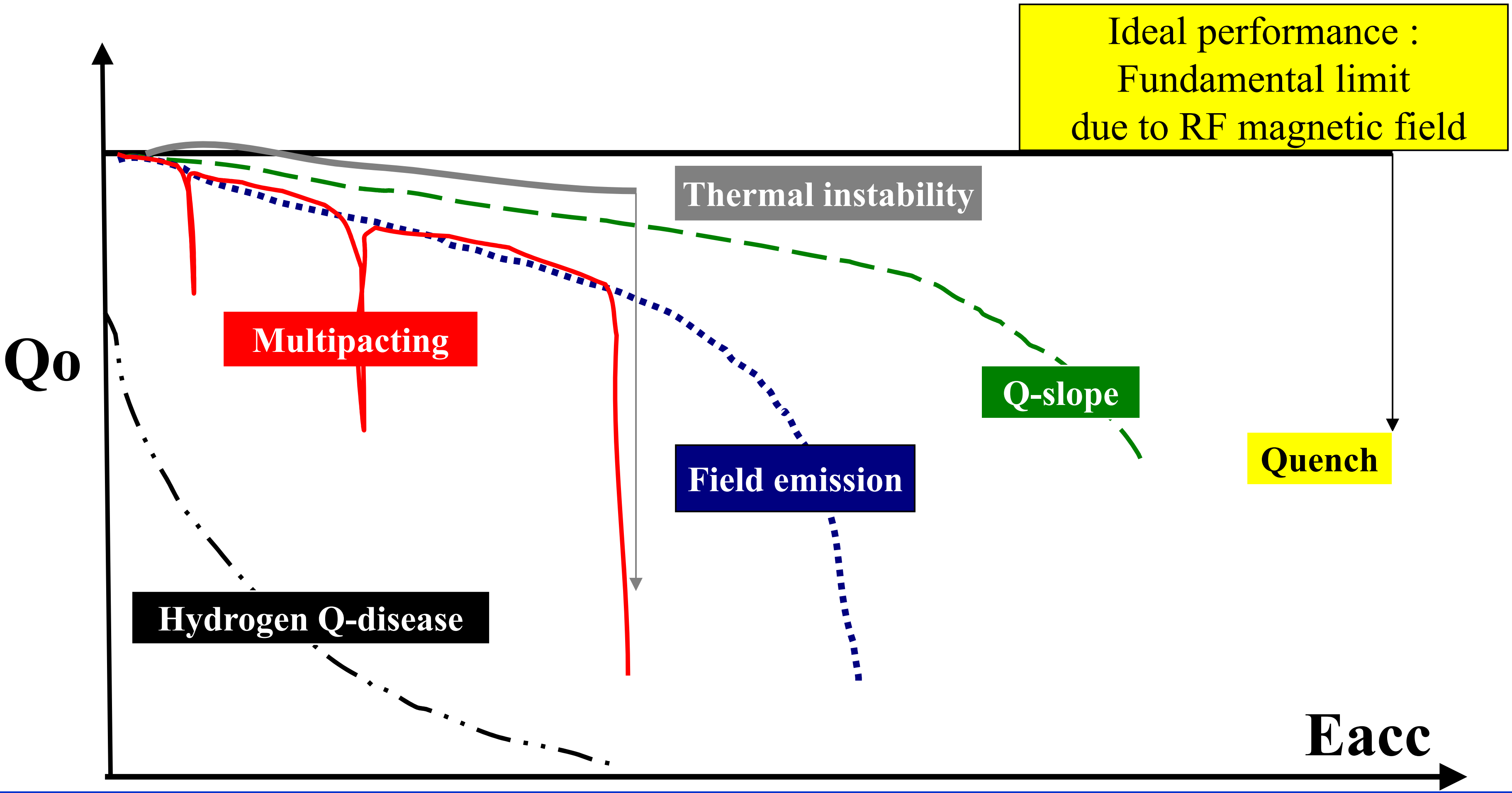
Surface current flows in very shallow skin surface (δ).

➡ *Cavity performance strongly depends on the surface.*

Thermal conductivity @ superconducting state is very small.

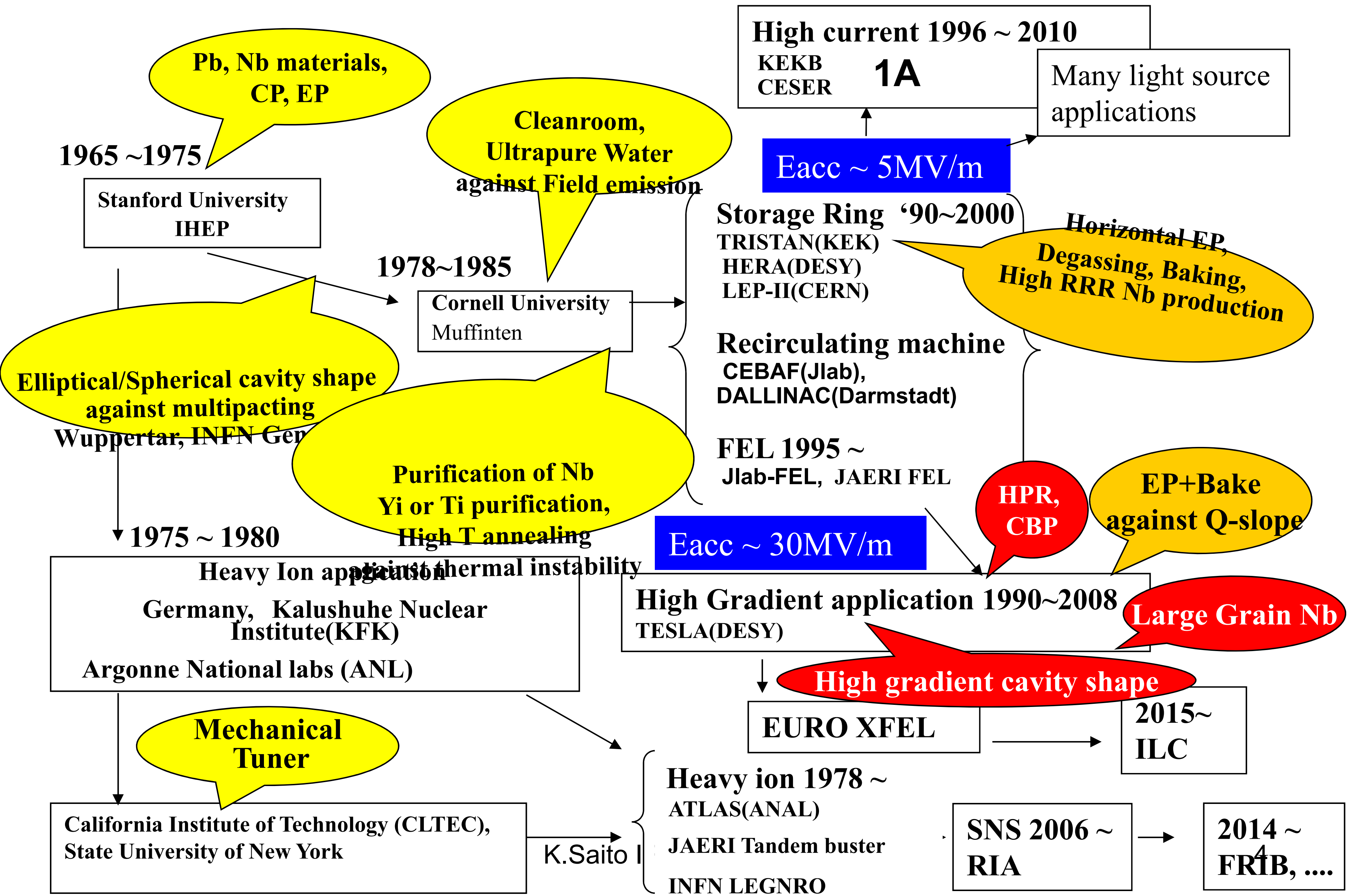
➡ *High thermal conductivity of the cavity wall @ low temperature is very important.*

Limited SRF Cavity Performance

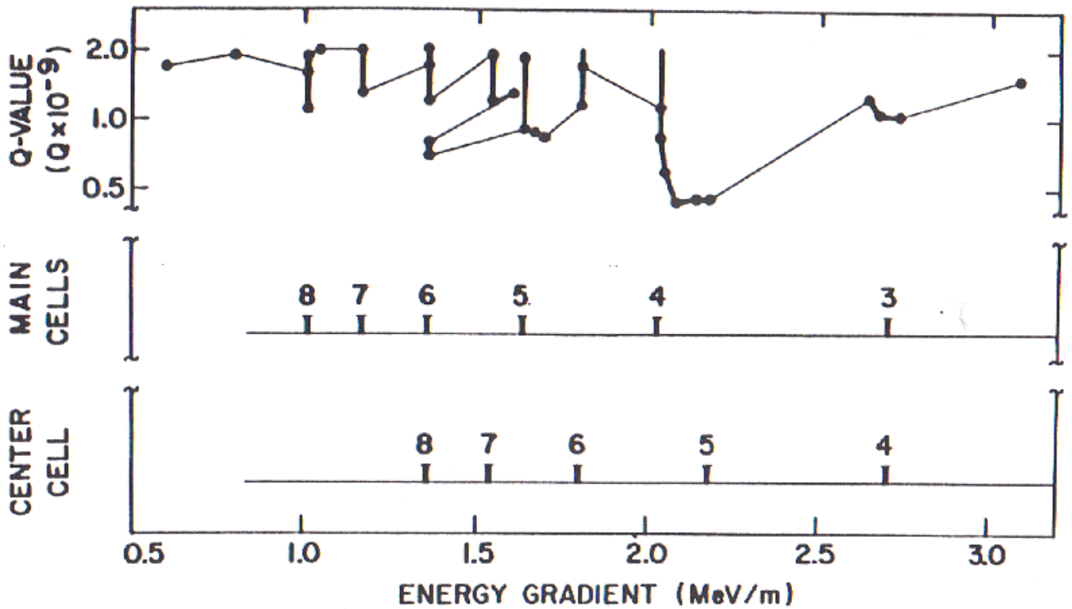


Field emission and Multipacting are related to surface contamination, which are mitigated by making clean SRF surface.
Thermal instability occurs at surface defects, which is suppressed by using high thermal conductivity Nb: High pure niobium.
Hydrogen Q-disease happens by niobium-hydride doped hydrogen during surface processing. This is cured by hydrogen degassing.

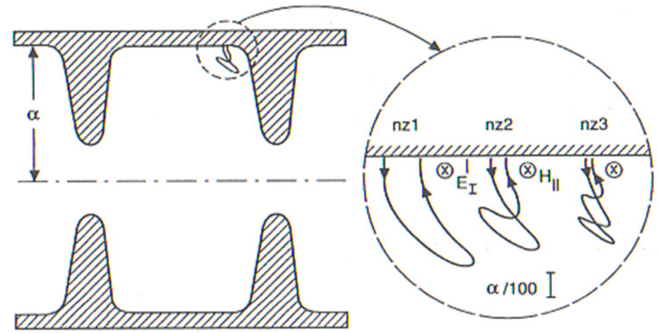
Understanding &Technologies Over Past 50 Years



Multipacting

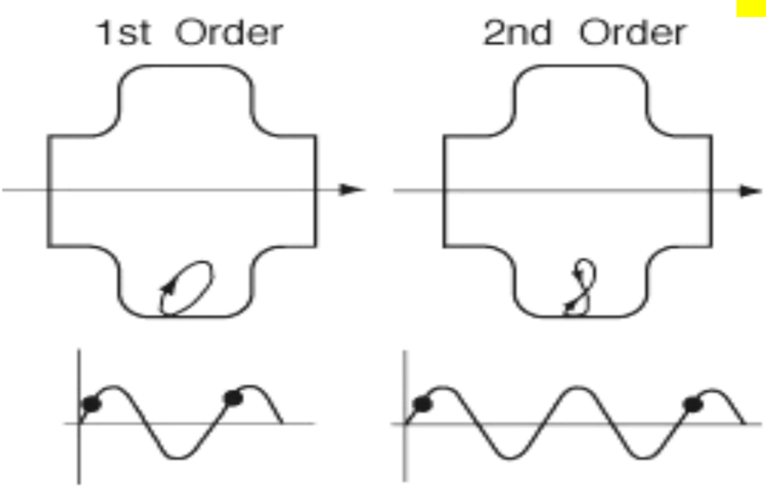


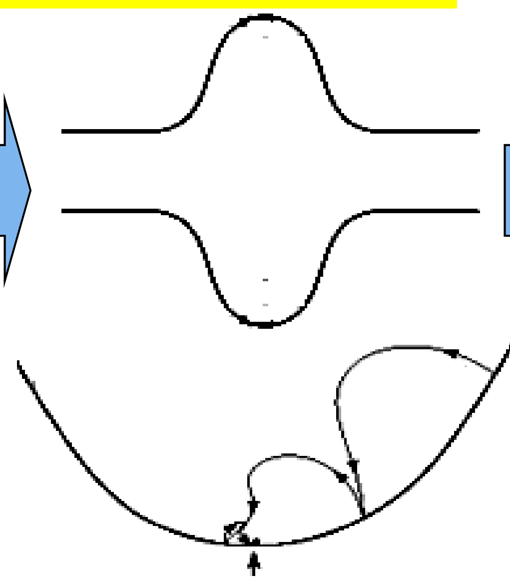
MP limited the gradient seriously in the early SC cavity R&D in Stanford Uni.



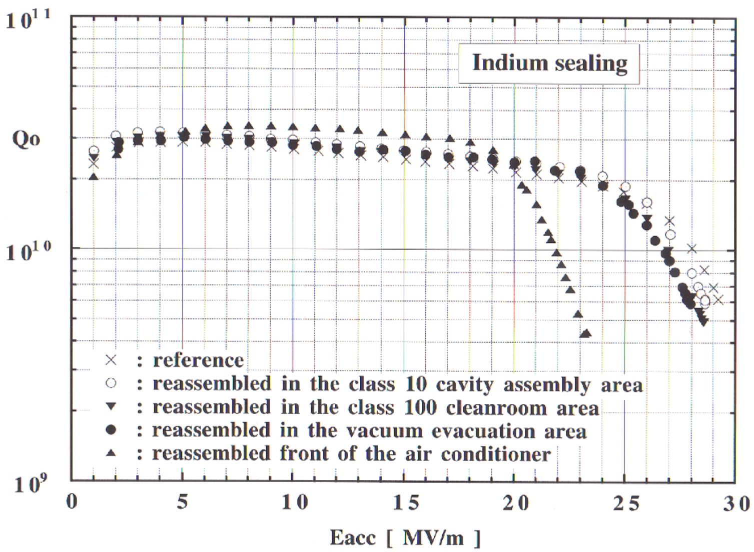
1 point MP

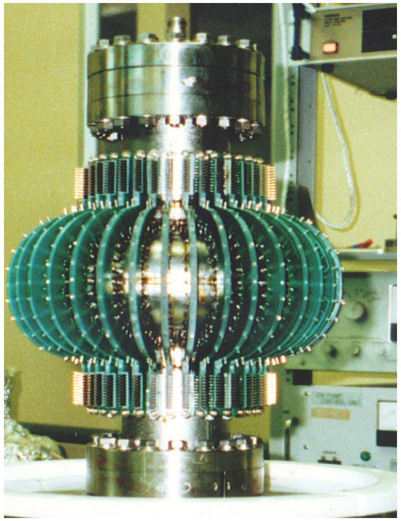
Courtesy of H.Padamsee

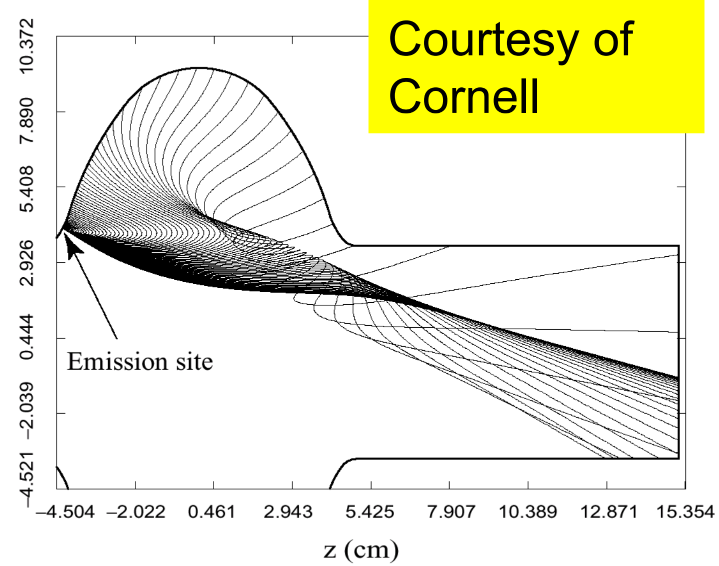


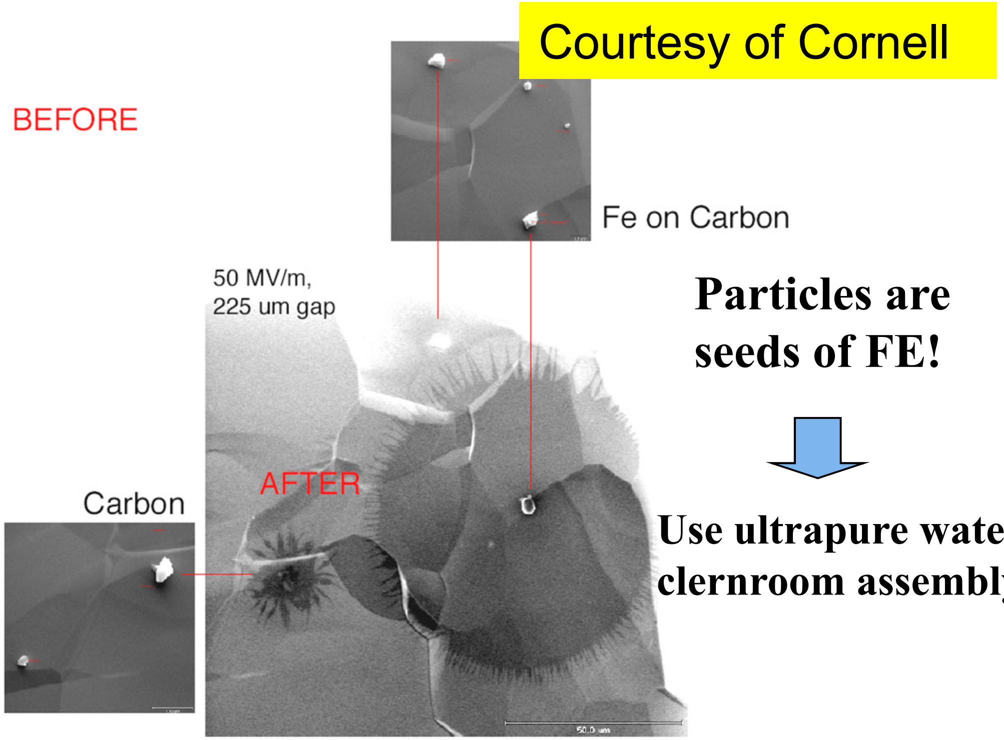


SRF Clean Surface by Adopting Semiconductor Technologies







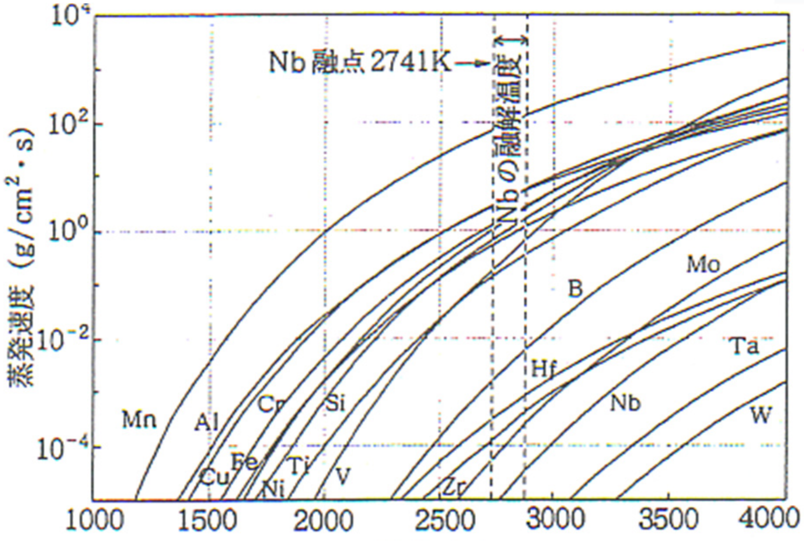


Particles are seeds of FE!

⇩

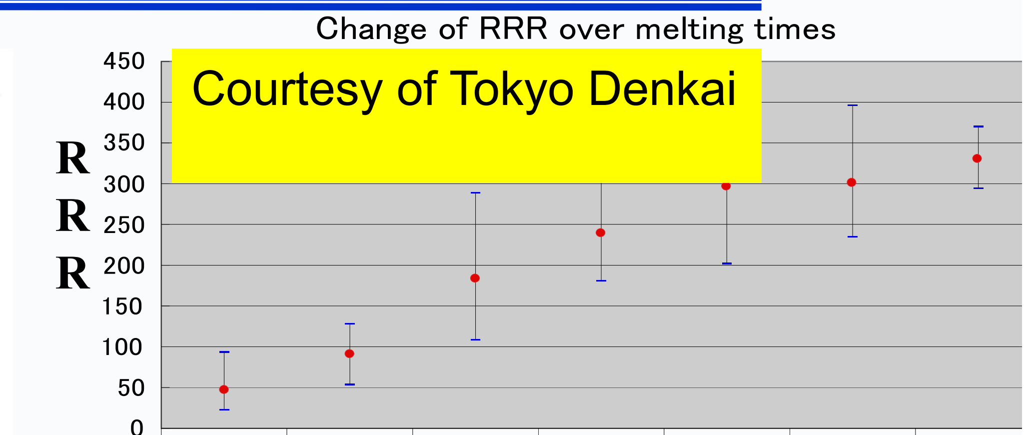
Use ultrapure water, clernroom assembly

Vendor High Purity Nb Material Production



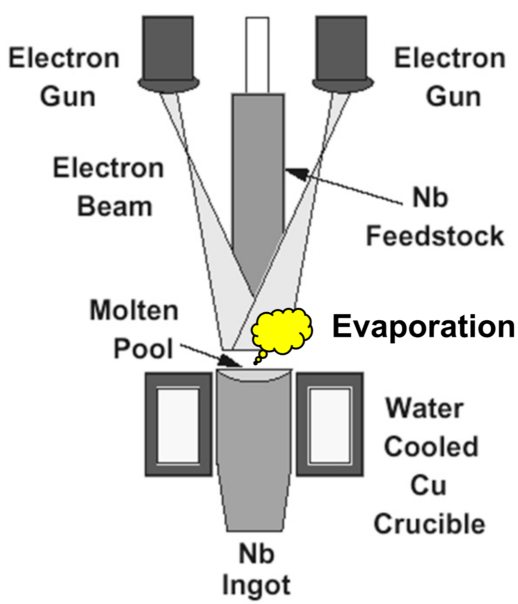
T [K]

Vapor Pressure vs. T



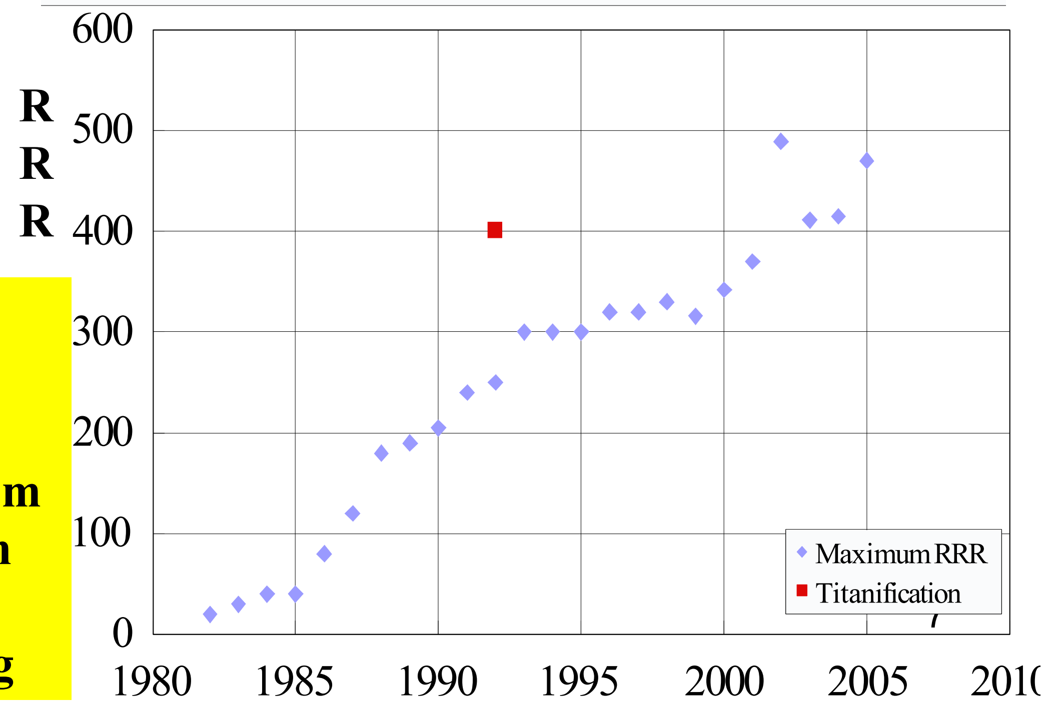
	A/R	1	2	3	4	5	6
Max	93	128	289	323	378	396	370
Average	46	90	183	240	296	301	329
Min	23	54	109	181	202	235	295

Melting Cycles

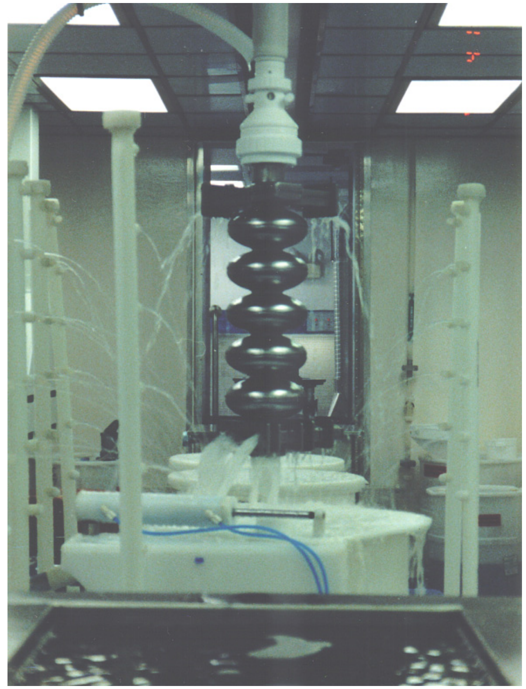


Crucial conditions

1) higher vacuum
2) larger molten surface
3) multi-melting

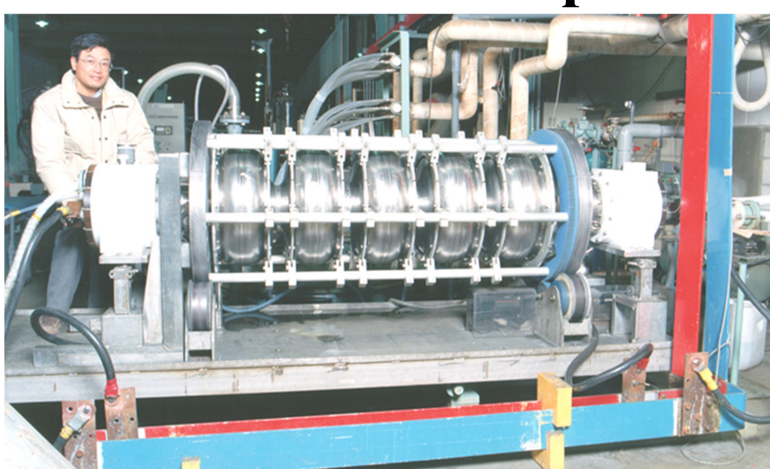


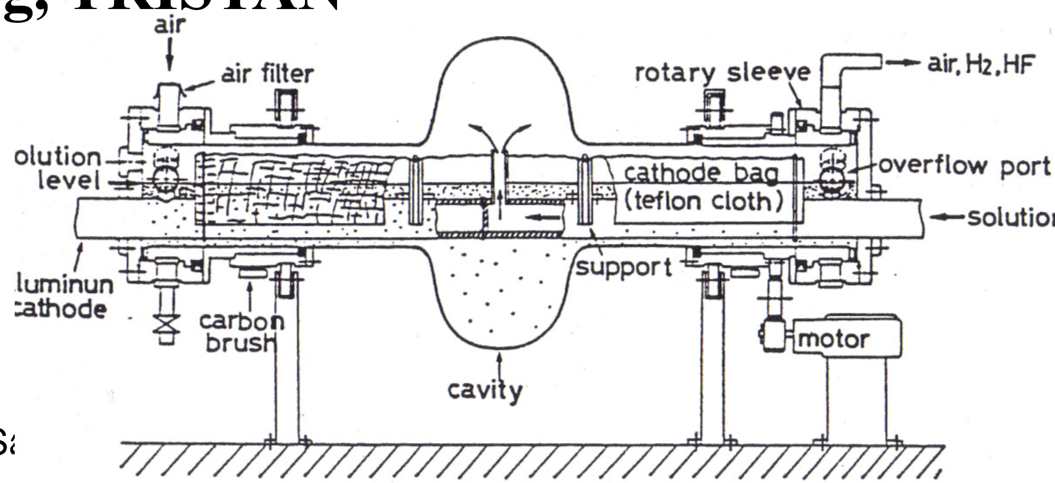
Chemical Processing for Production Cavities



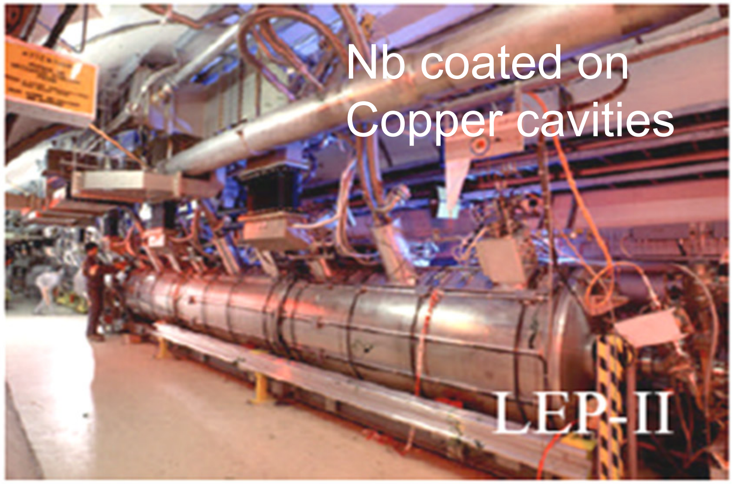
Buffered Chemical Polishing, CEBAF

Horizontal Electropolishing, TRISTAN

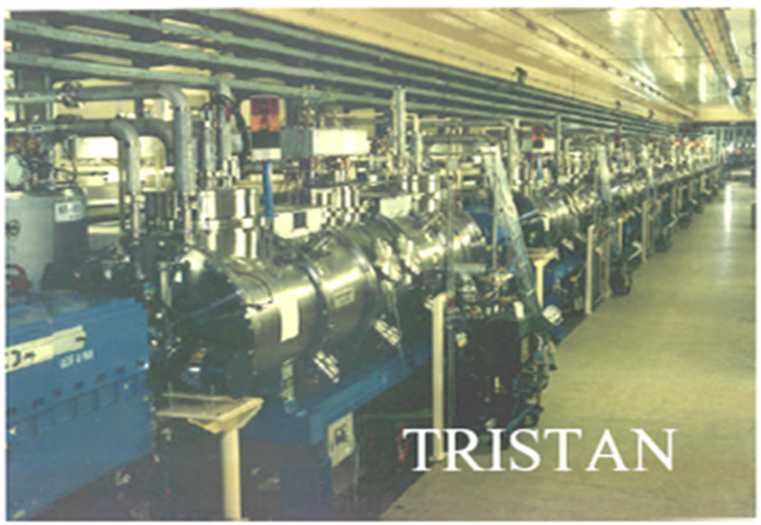


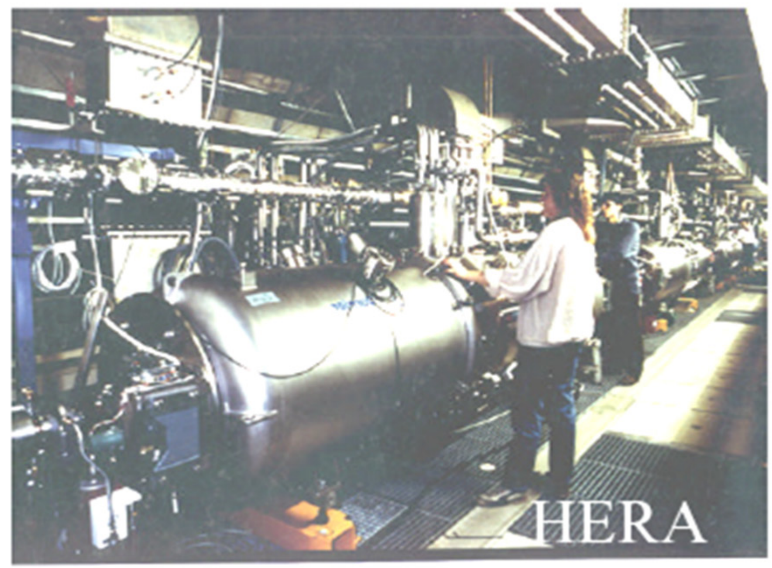


World Wide SC Accelerators in 1990'



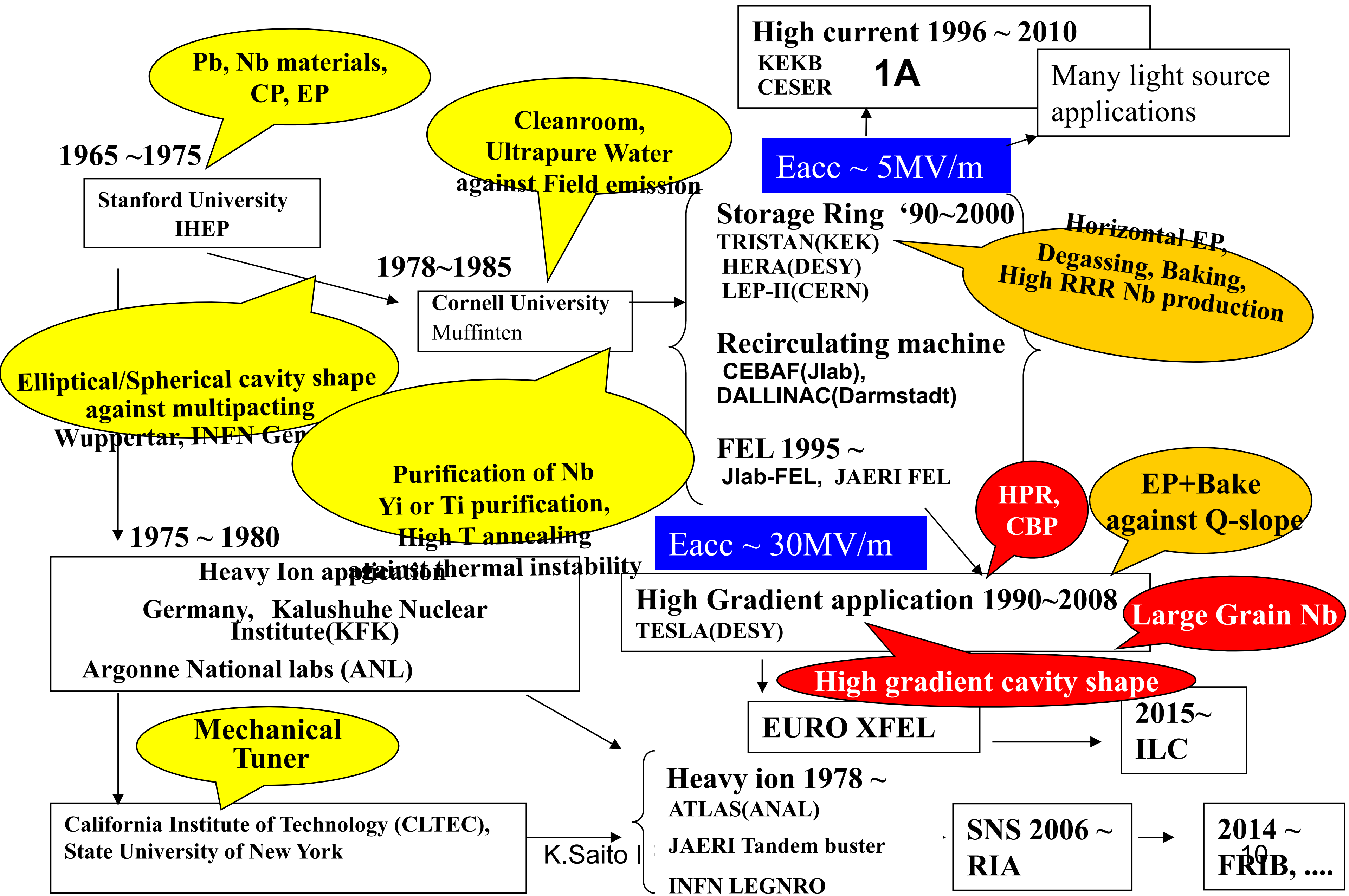
SOUTH LINAC CRYOMODULES





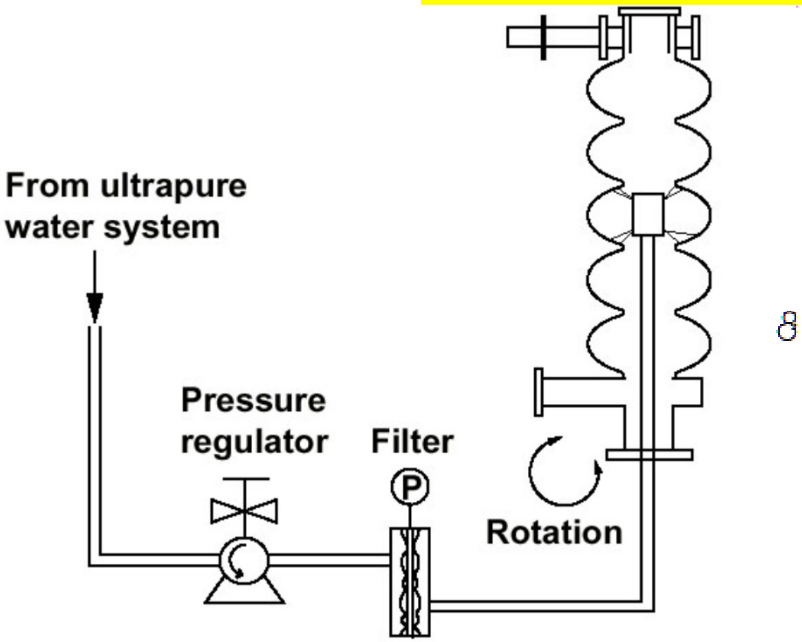
~ 5MV/m CW operation

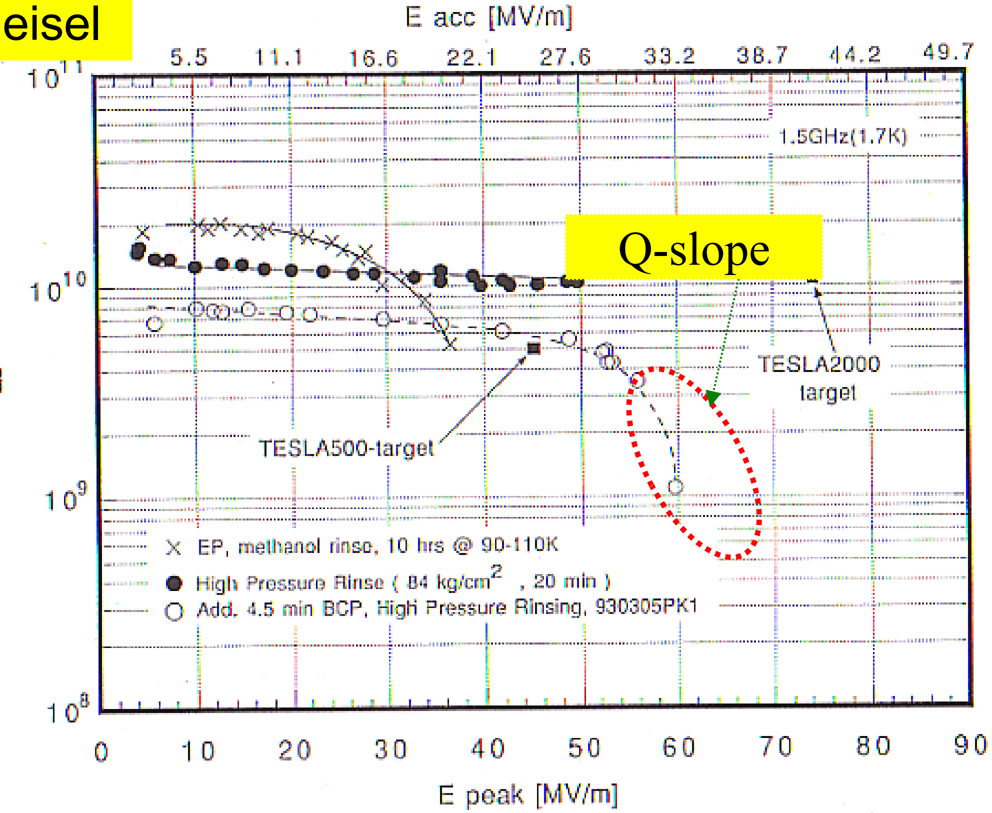
Understanding &Technologies over 50 years



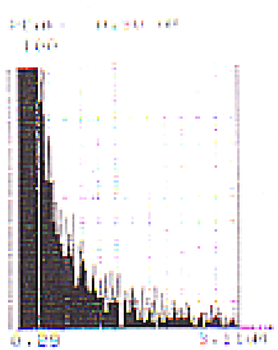
High Pressure Water Rinsing (HPR)

Courtesy of P.Kneisel



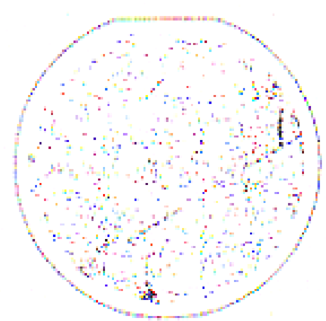


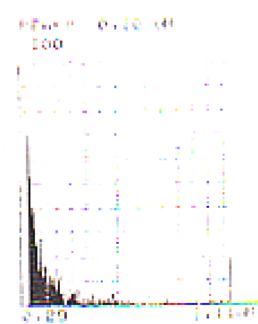
TRISTAN rinsing method



Particle size	Count
0.30-1.20 µm	5825
1.20-2.01 µm	405
2.01-3.00 µm	2720
> 3.00 µm	1069
Total	10019

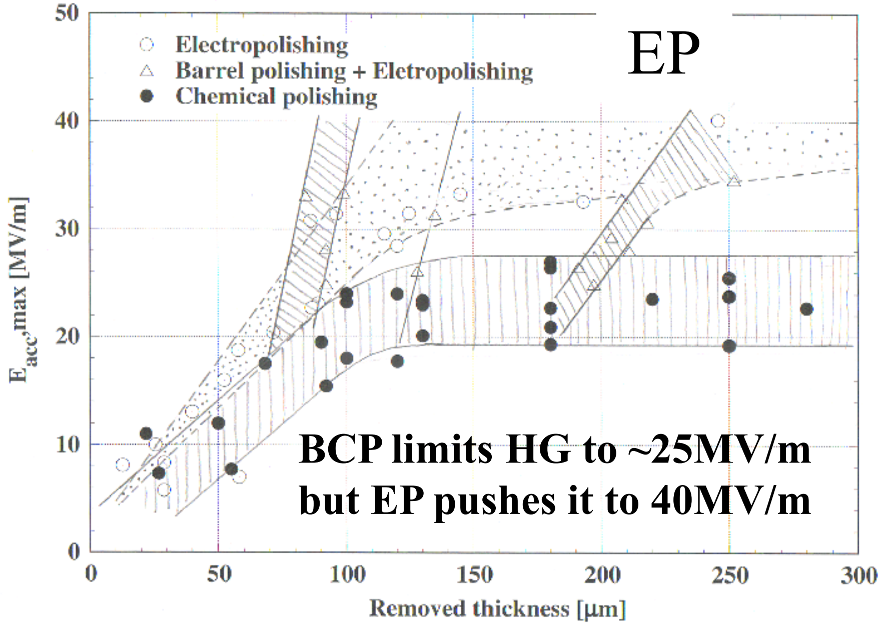
HPR rinsing

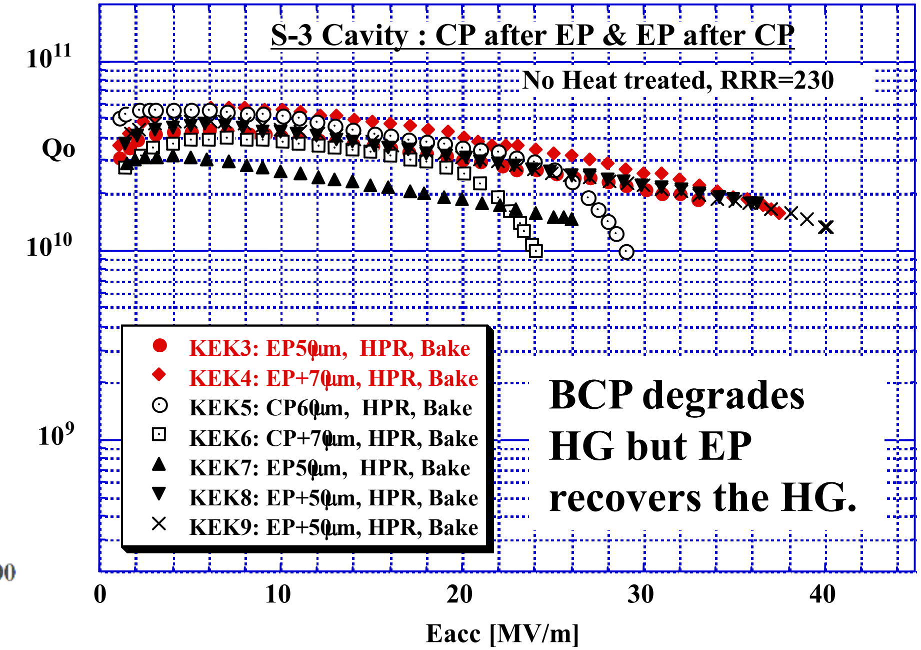


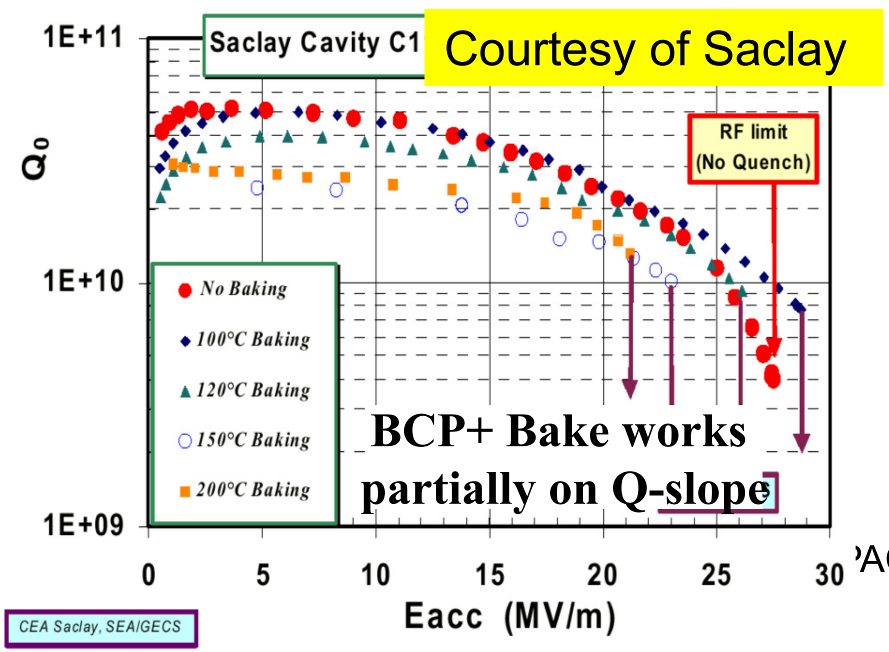


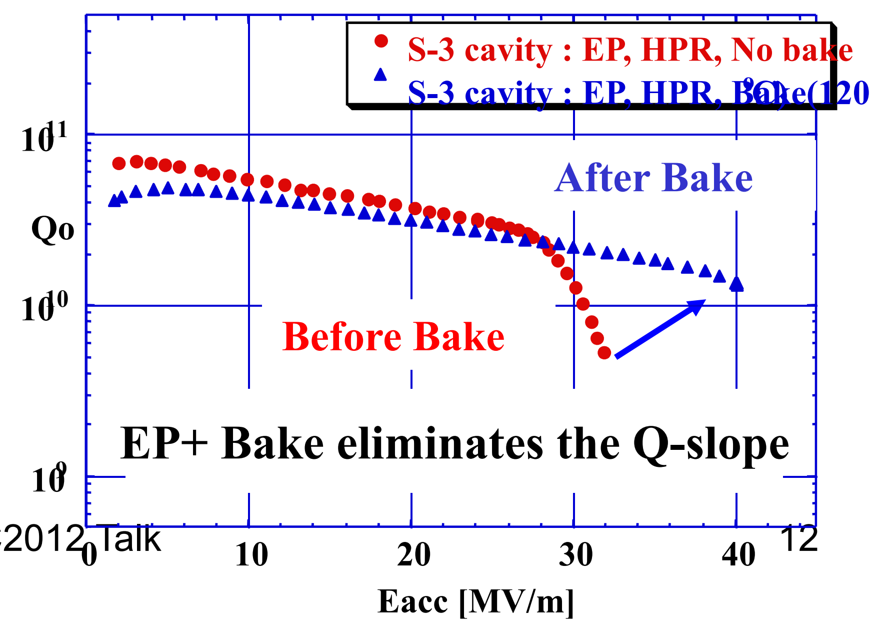
Particle size	Count
0.30-1.20 µm	646
1.20-2.01 µm	52
2.01-3.00 µm	282
> 3.00 µm	37
Total	1017

Superiority of EP on HG and Baking Effect of High Field Q-Slope







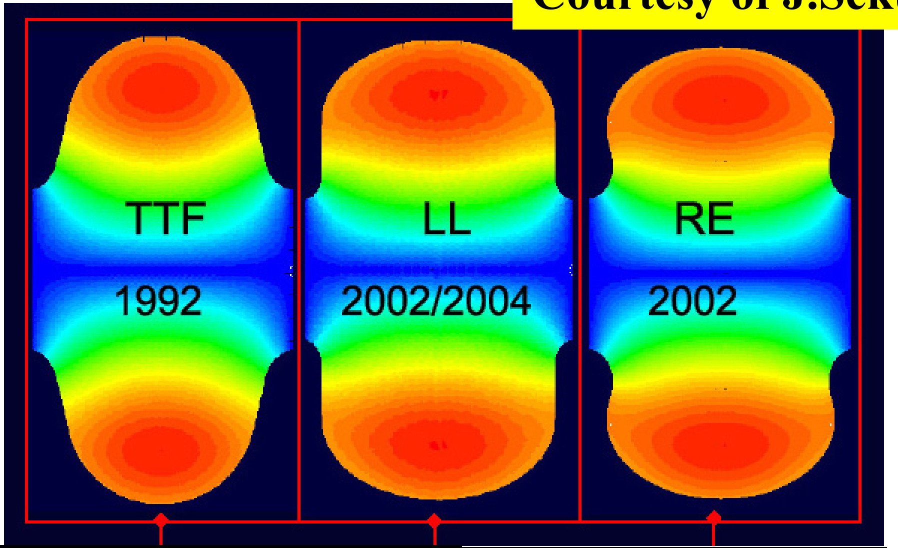


High Gradient Cavity Shape for 50MV/m

Cavity shape designs with low Hp/Eacc

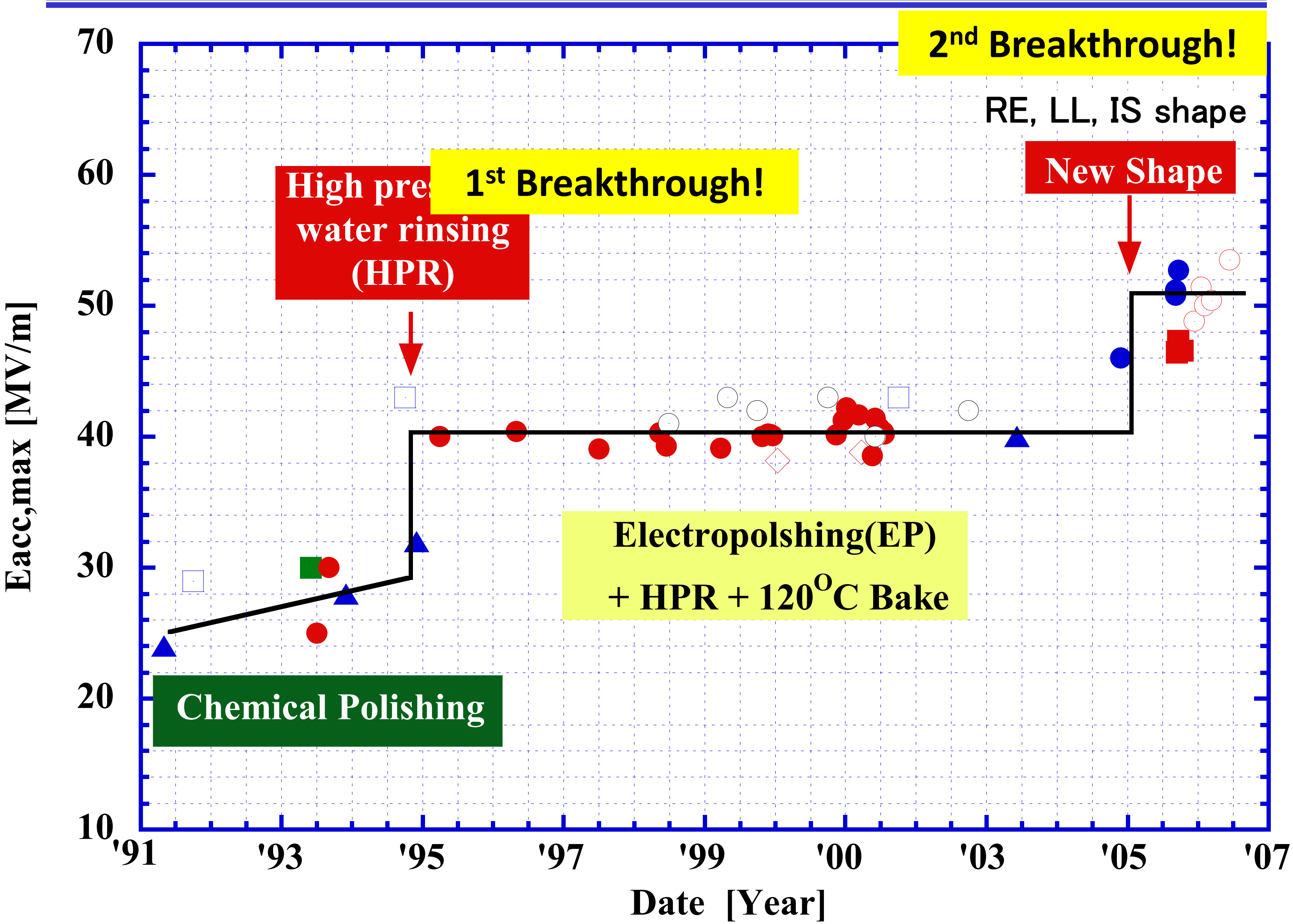
Courtesy of J.Sekutowicz

TTF: TESLA shape
Reentrant (RE): Cornell Univ.
Low Loss(LL): JLAB/DESY
Ichiro−Single(IS): KEK



	TESLA	LL	RE	IS
Diameter [mm]	**70**	**60**	**66**	**61**
Ep/Eacc	**2.0**	**2.36**	**2.21**	**2.02**
Hp/Eacc [Oe/MV/m]	**42.6**	**36.1**	**37.6**	**35.6**
R/Q [W]	**113.8**	**133.7**	**126.8**	**138**
G[W]	**271**	**284**	**277**	**285**
Eacc max	**41.1**	**48.5**	**46.5**	**49.2**

History of upgraded gradient in SRF



12GeV CEBAF Upgrade by State-of-Art

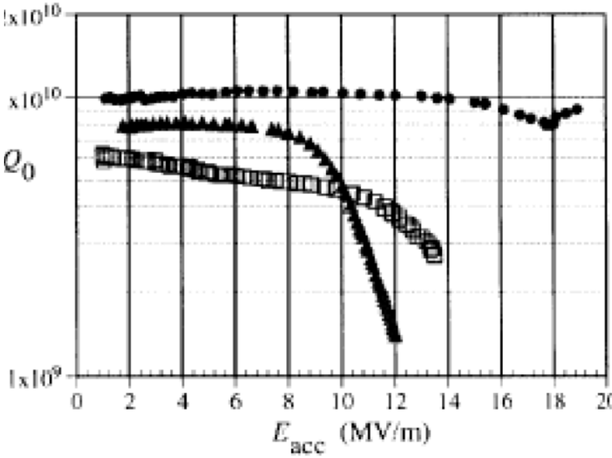
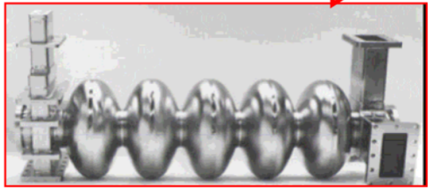
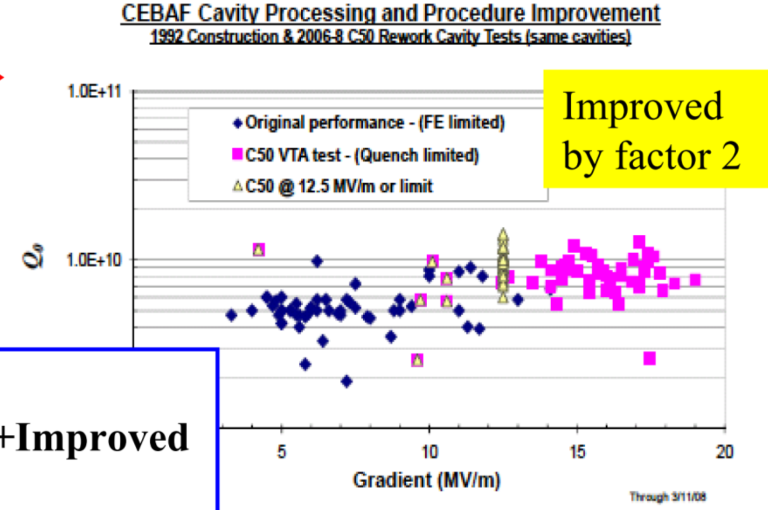


Figure 1. Typical cavity performance in vertical testing.

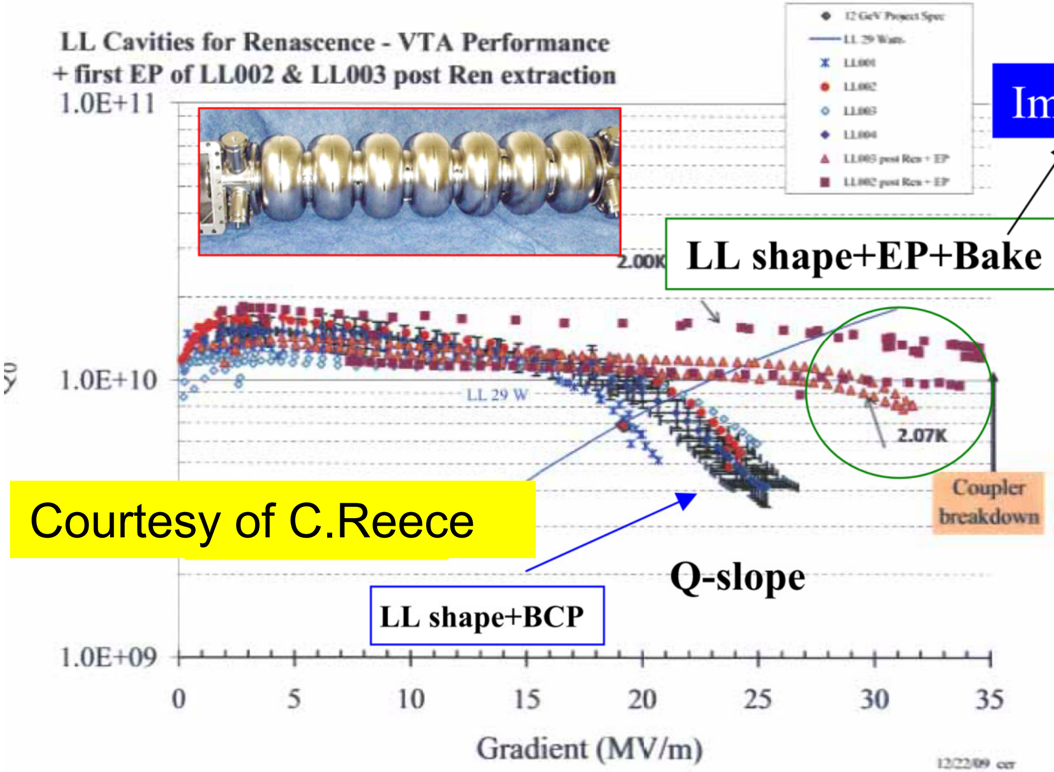
Mainly HPR





Improved by factor 2

By the state-of-the-art procedures:BCP+HPR+Improved cavity clean assembly



Improved by factor 4

LL shape+EP+Bake

Q-slope

LL shape+BCP

Courtesy of C.Reece

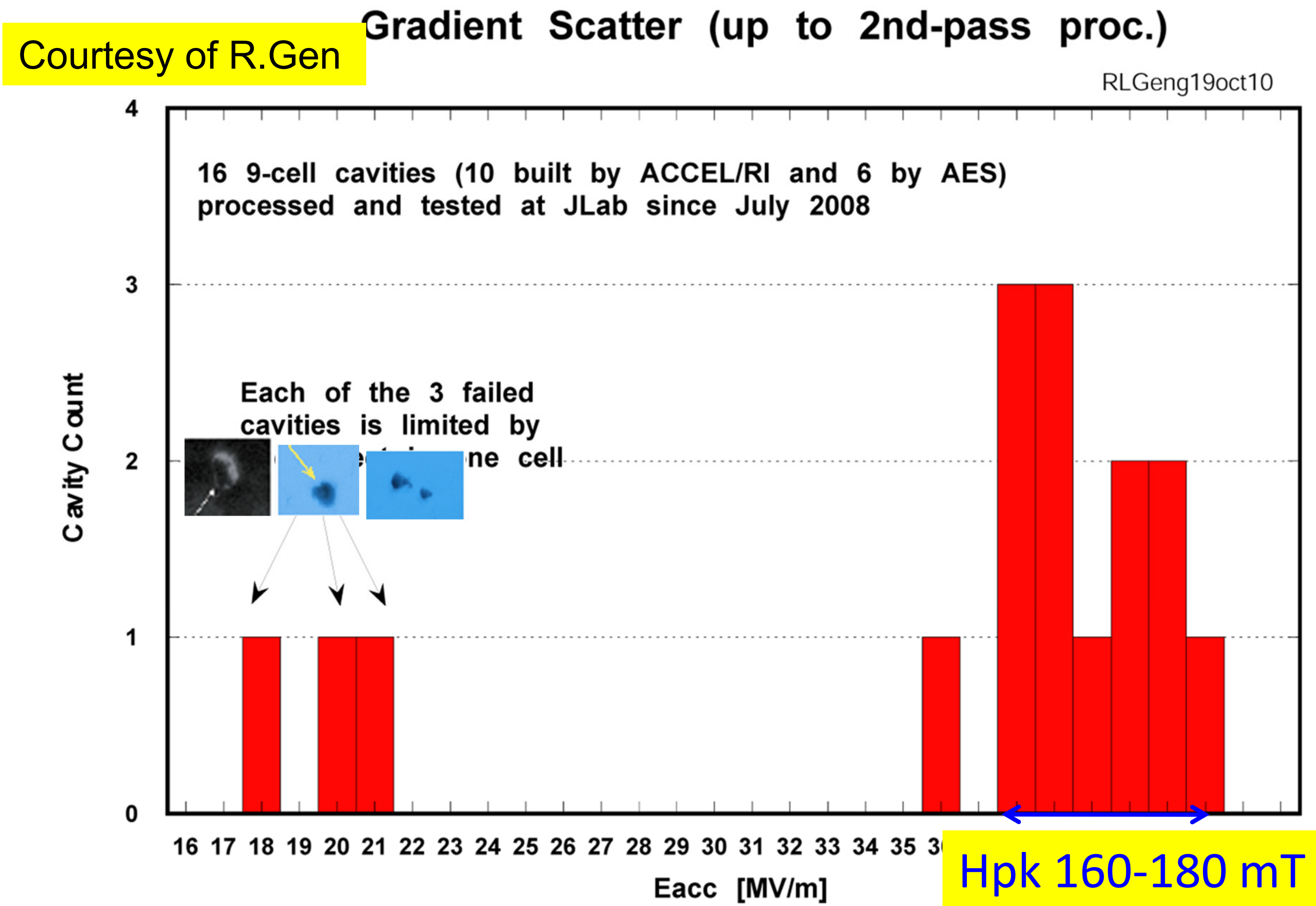
1) Higher gradient due to LL shape.

2) High Q performance due to LL shape

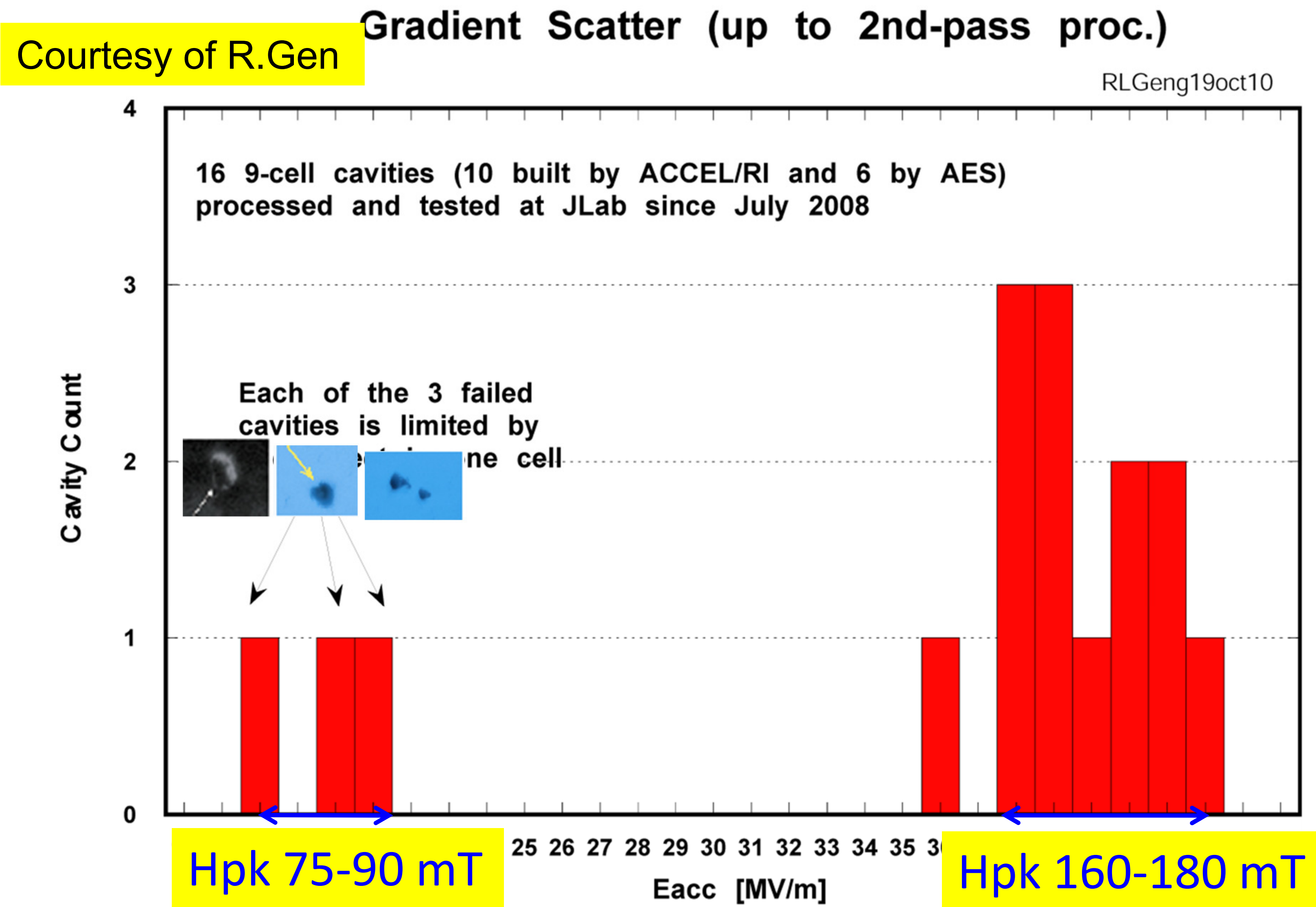
3) Possible 25MV/m operation by EP+Baking, which brings a big operation margin.

4) State-of-art technology pushes the performance very much.

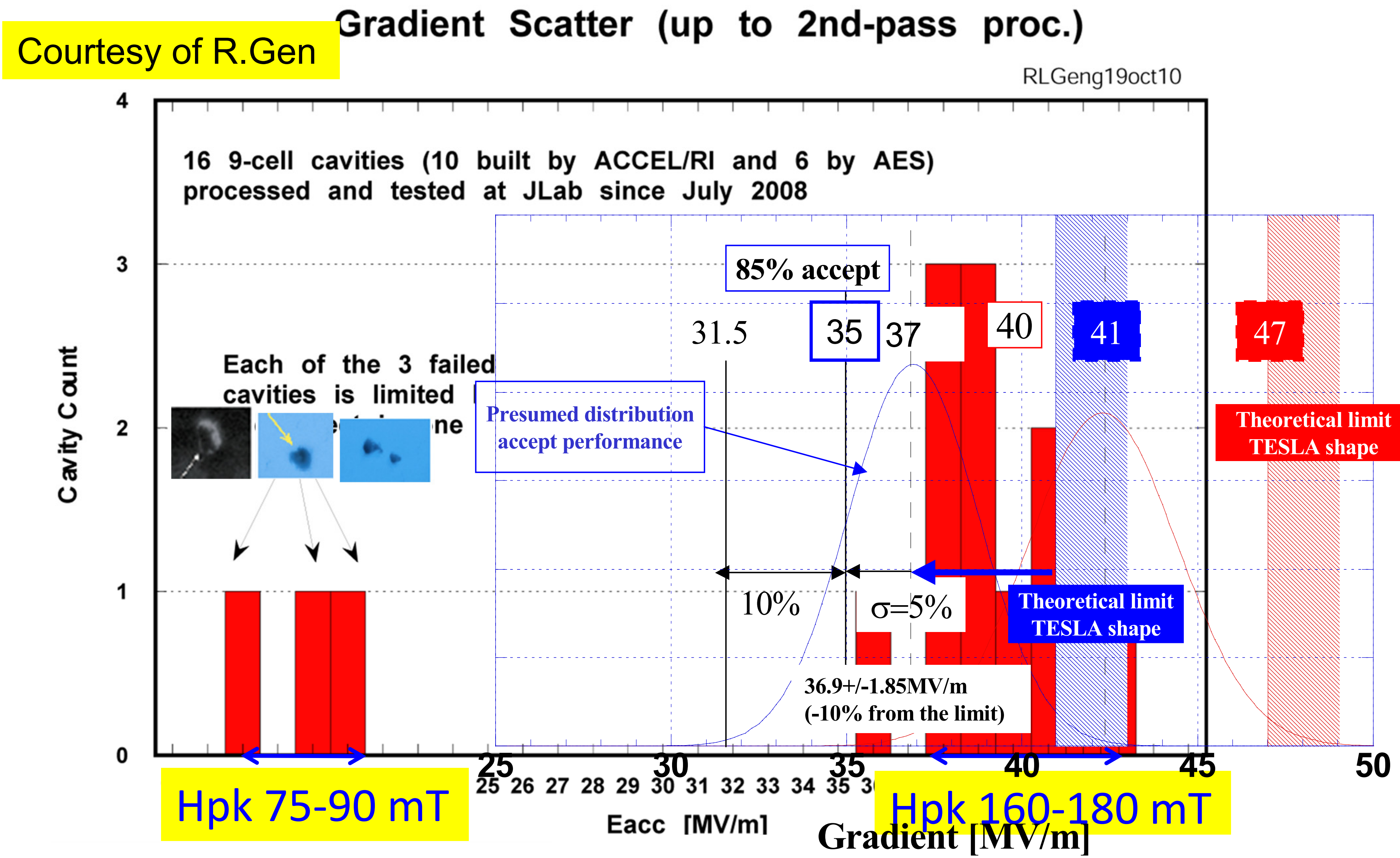
ILC Baseline Gradient and Recent Achievement



ILC Baseline Gradient and Recent Achievement



ILC Baseline Gradient and Recent Achievement



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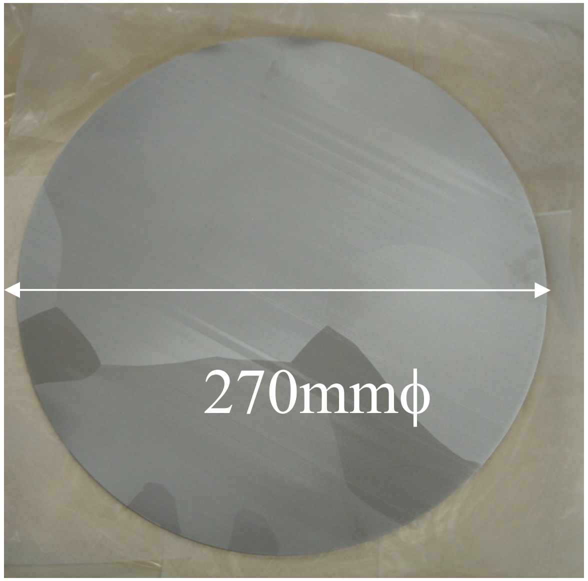
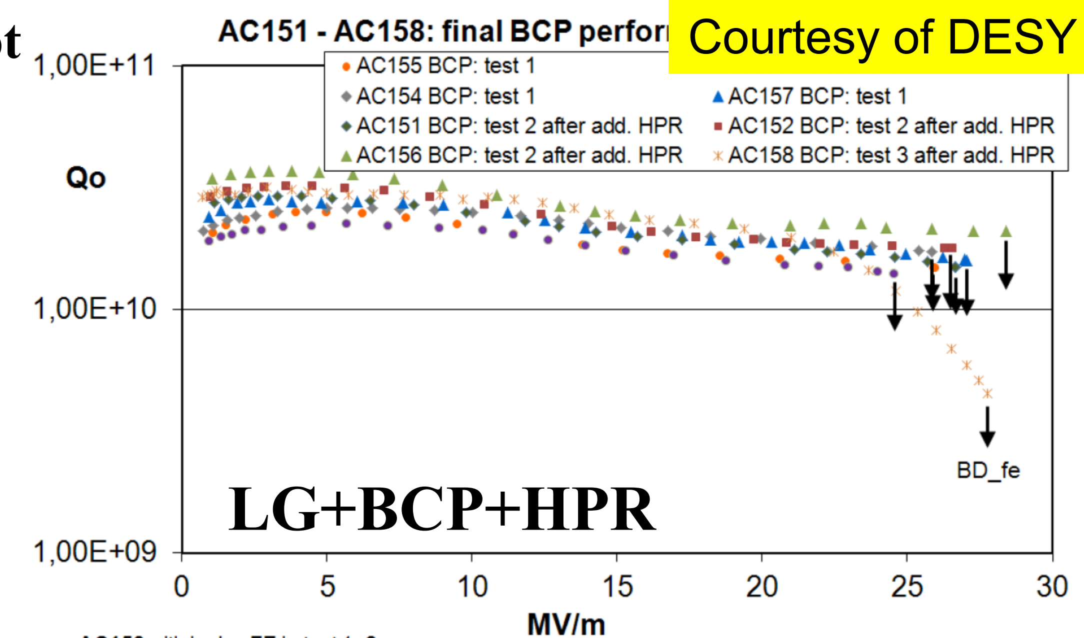
Large Grain Nb Cavities

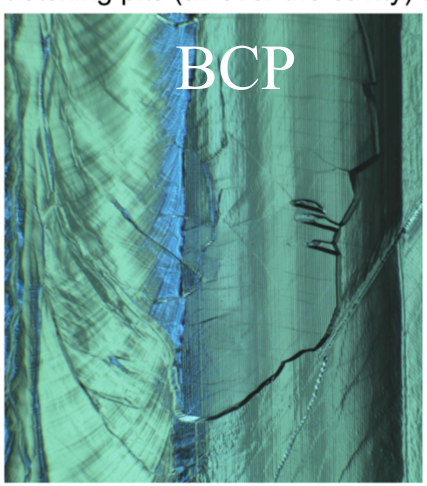
Directly sliced Nb sheet from Ingot





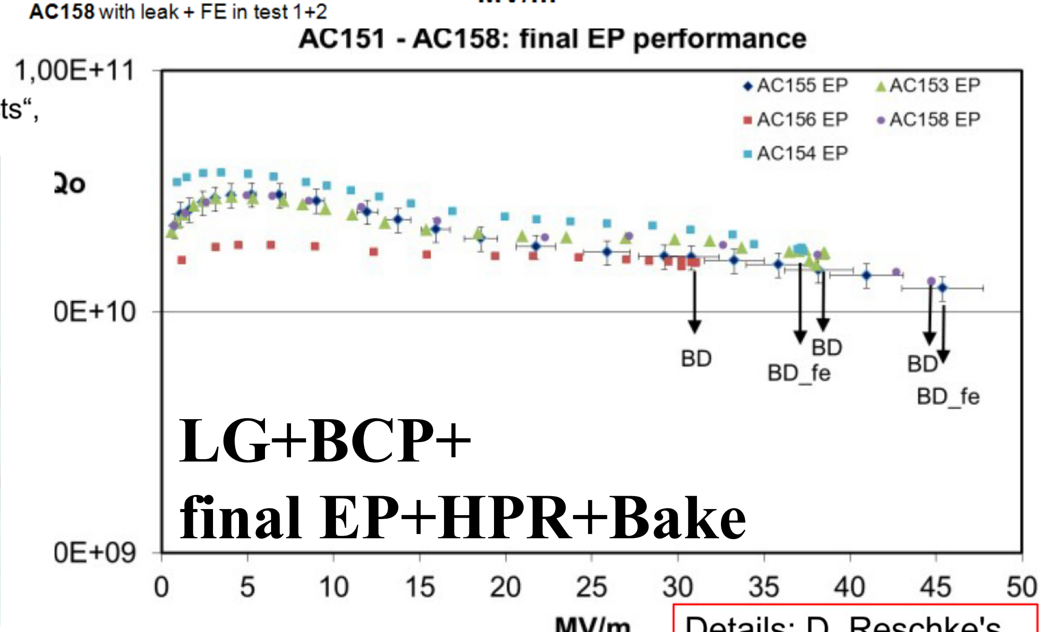
AC158 with leak + FE in test 1+2

Quench-sites inspected in AC151-AC158 so far: no „obvious defects", just etching pits (all over the cavity) and grain boundaries



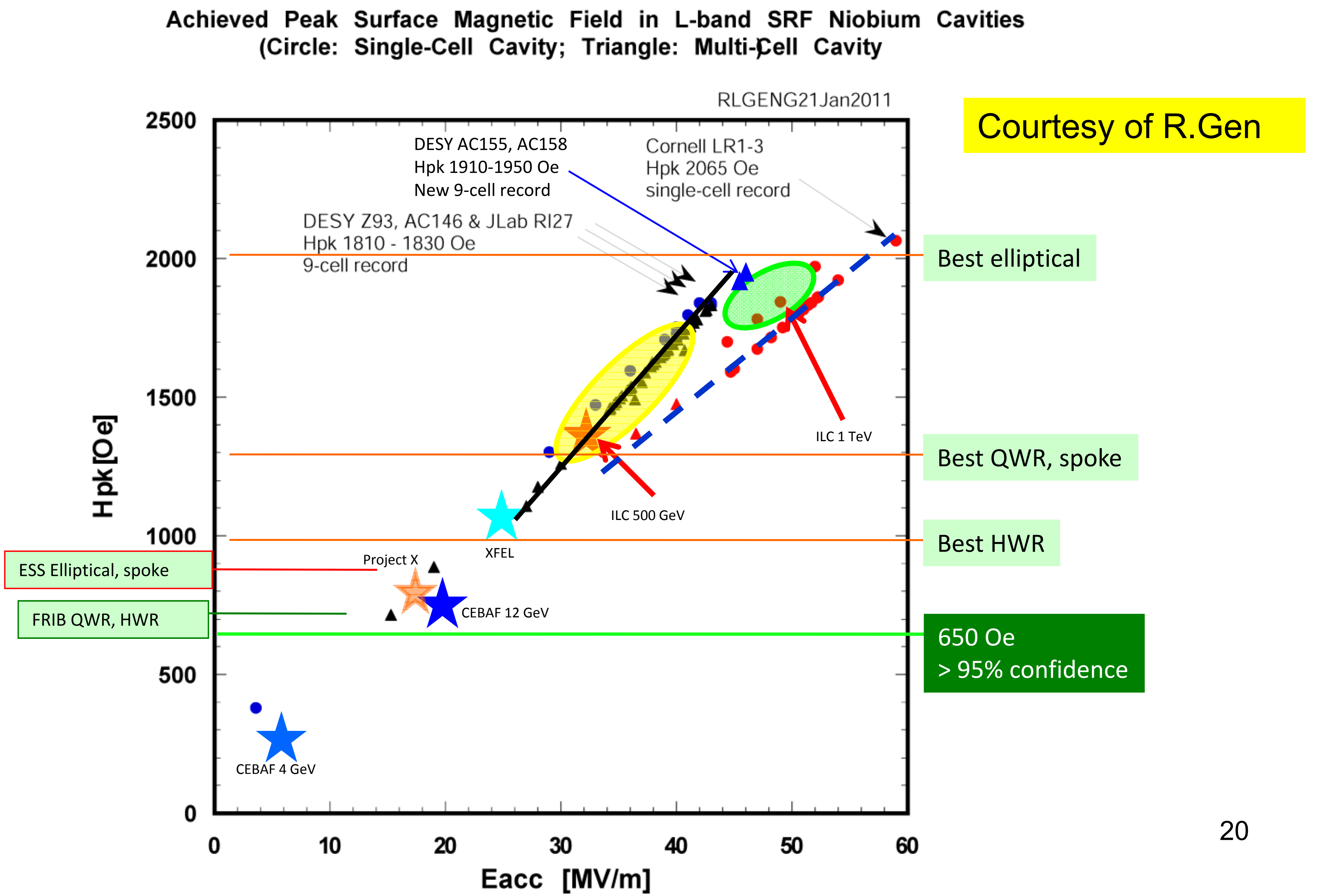
After BCP: sharp edges

After EP: smoothed edges



Details: D. Reschke's poster TUPO046

Improvement of High Gradient in Various SRF Fields



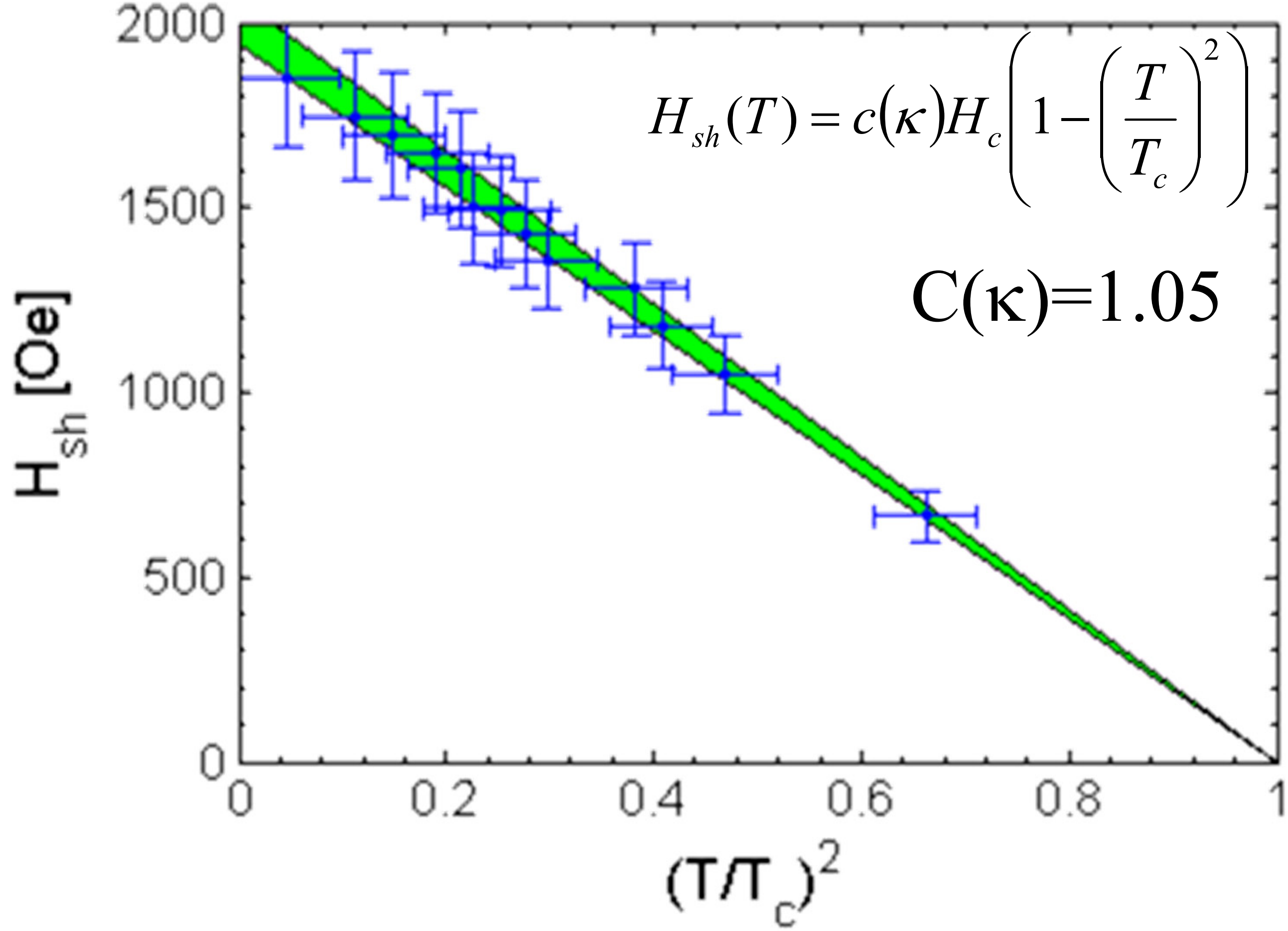
Fundamental Field Limit with Nb Cavity

Courtesy of Cornell

Superheating Model

$$H_{sh}(T) = c(\kappa) H_c \left(1 - \left(\frac{T}{T_c} \right)^2 \right)$$

C(κ)=1.05



$$E_{acc} = H_{sh} / (H_p / Eacc) = \frac{2000(Oe)}{36(Oe/[MV/m])} \approx 56MV/m$$

Future Prospects in SRF Cavity

High gradient shape
~15% upgrade

+

Improved space factor
~10% upgrade

+

Martial
improve
~10% upgrade

Nb bulk Cavity   50~60MV/m fundamental Limit: Vortex entry @ Hc1

Exploring New Materials for 100~200MV/m & High Q

Stopped Nb_3Sn(~1995) by weak link grain boundary effect

or

Failed in HTS (1990') due to fundamental reason (d-wave)

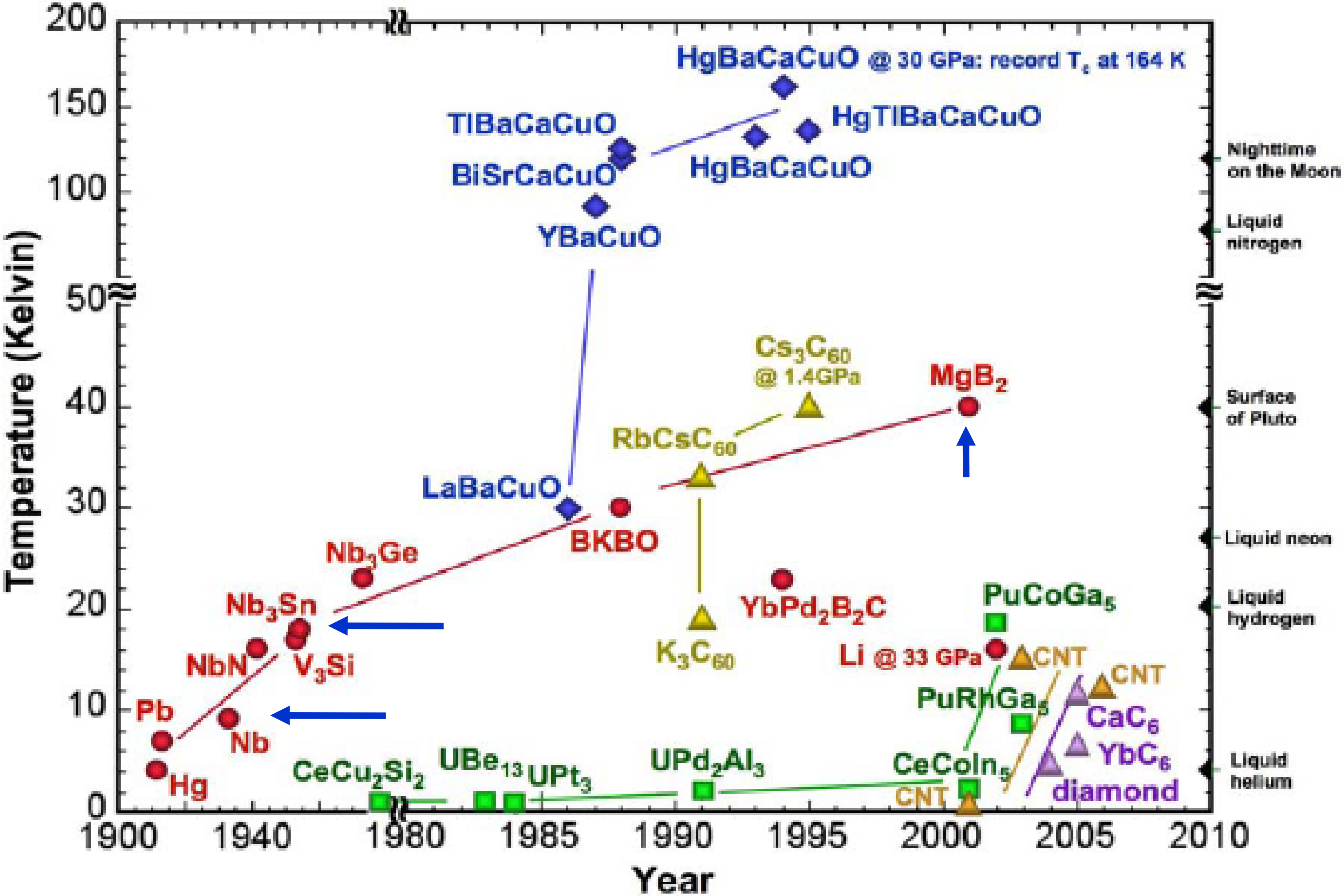
Thin Film Multi -Layer Cavity

Alex Gurevich, APL 88, 012511 (2006)

20~30 years beyond

Understand
Substrate boundary ← Niobium Coated Film Cavity → Develope best coating
technology

Superconducting Materials



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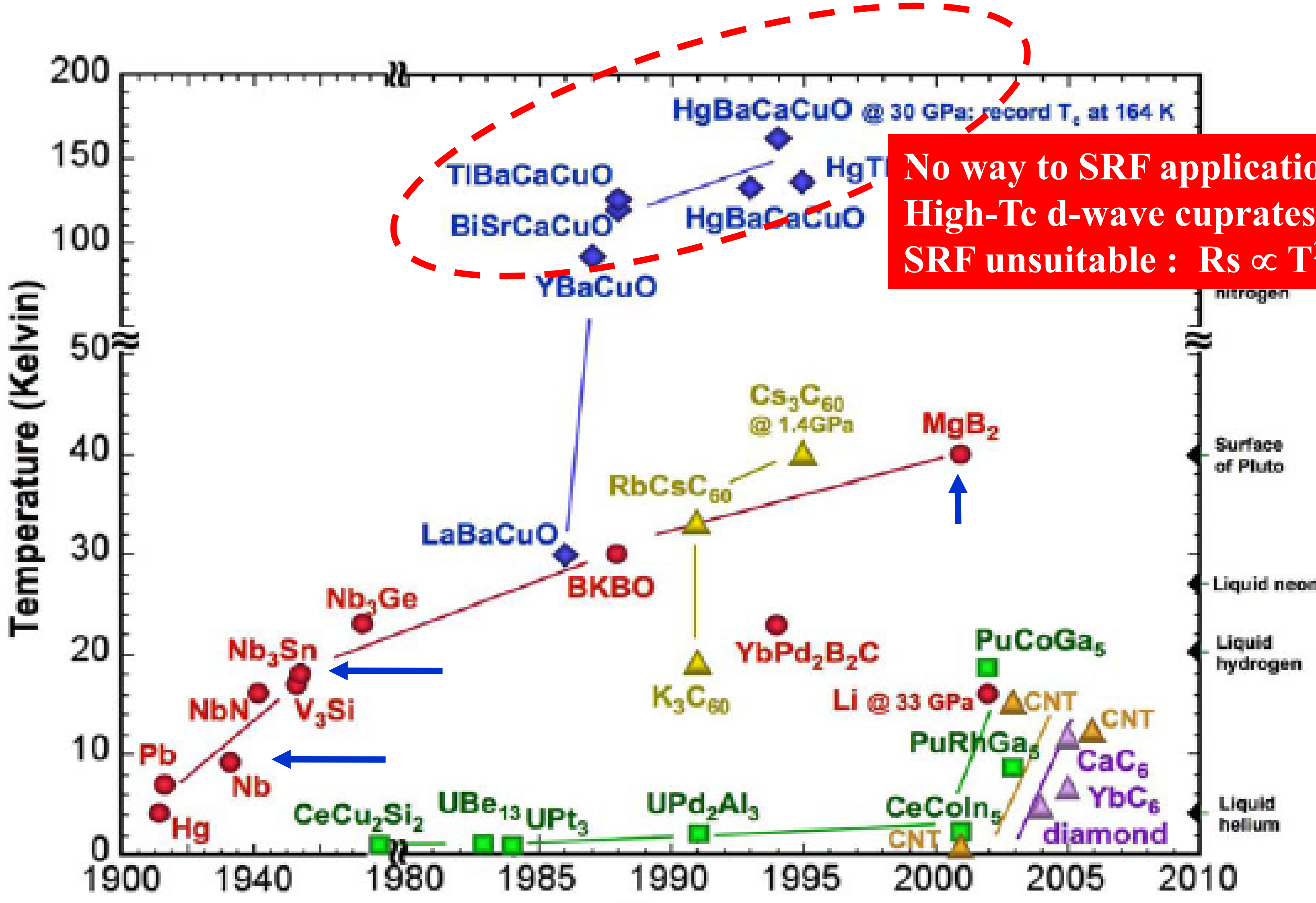
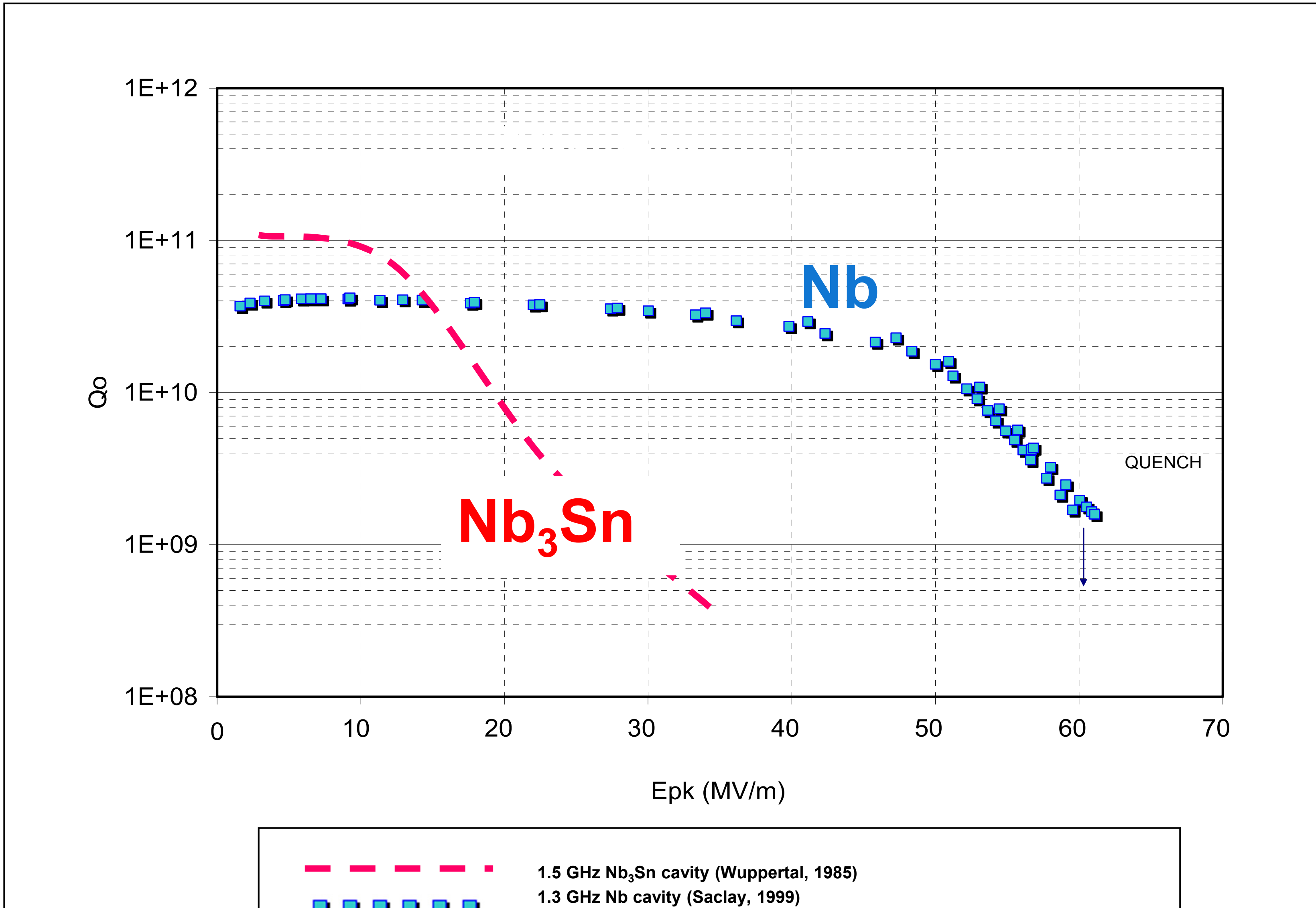
Superconducting Materials



No way to SRF application : High-Tc d-wave cuprates are SRF unsuitable : $R_s \propto T^2$

Classic HTSs are s-wave superconductors: $R_s \sim \exp(-\Delta/k_BT)$.
If weak link mechanism is solved, excellent performance is expected.

Superconducting Materials



ation :
tes are
c T^2

Nb_3Sn is a classic HTS, however, not yet achieved the expected performance due to weak link mechanism at grain boundary.

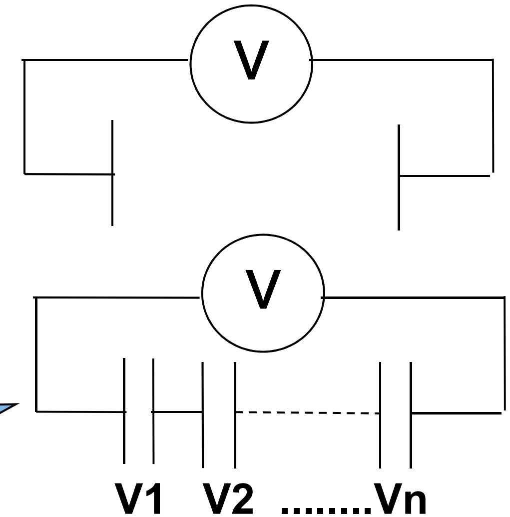
Alex's Idea of TFML(complicated)

Overcoming niobium limits (A.Gurevich, 2006) :

Courtesy of A. Gurevich

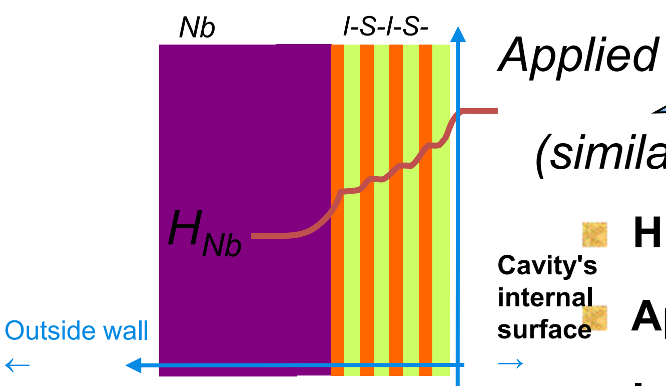
- **Keep niobium but shield its surface from RF field to prevent vortex penetration**
- Use nanometric films (w. d < λ) of higher Tc SC :
  => H_{C1} enhancement
- Example :

NbN , ξ = 5 nm, λ = 200 nm



H_{C1} = **0,02 T**

20 nm film => H'_{C1} = **4,2 T** **x 200**



(similar improvement expected with MgB_2 or Nb_3Sn)

$$H_{Nb} = H_{appl}\, e^{-\frac{Nd}{\lambda}}$$

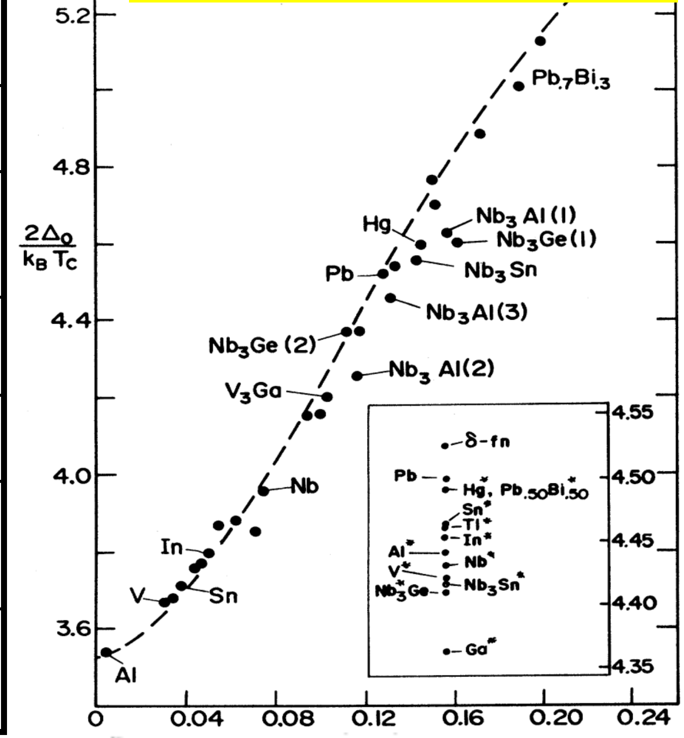
- **High H_{C1} => no transition, no vortex in the layer**
- **Applied field is damped by each layer**
- **Insulating layer prevents Josephson coupling between layers**
- **Applied field, i.e. accelerating field can be increased without**

  vortex nucleation
- **Thin film w. high Tc => low R_{BCS} at low field => higher Q_0**

Potential TFML Materials

Material	T_c (K)	H_c [T]	H_{c1} [mT]	H_{c2} [T]	$\lambda(0)$ [nm]	Δ [meV]
Nb	9.2	0.2	170	0.4	40	1.5
$B_{0.6}K_{0.4}BiO_3$	31	0.44	30	30	160	4.4
Nb_3Sn	18	0.5	40	30	85	3.1
NbN	16.2	0.23	20	15	200	2.6
MgB_2	40	0.32	20-60	3.5-60	140	2.3; 7.1
$Ba_{0.6}K_{0.4}Fe_2As_2$	38	0.5	20	>100	200	>5.2

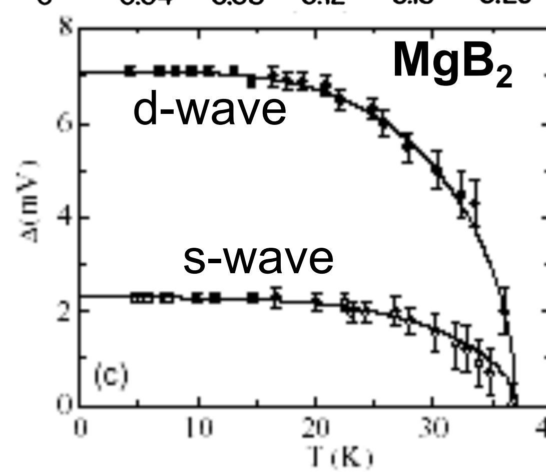
Courtesy of A.Gurevich



High-T_c d-wave cuprates are SRF unsuitable ($R_s \propto T^2$ instead of $R_s \propto \exp(-\Delta/T)$)

Large s-wave gap (good for SRF) is usually accompanied by low H_{c1} (bad for SRF)

K.Saito IPAC2012 Talk



M. Iavarone *et al.*, PRL 89, 187004 (2002)

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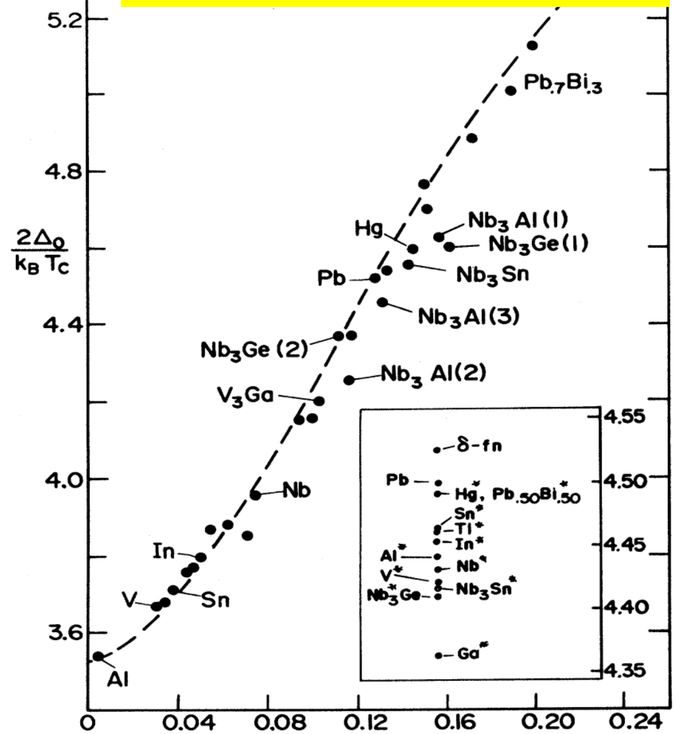
Nb_3Sn	18	0.5	40	[illegible]	85	3.1
NbN	16.2	0.23	20	15	200	2.6
MgB_2	40	0.32	20-60	3.5-60	140	2.3; 7.1
$Ba_{0.6}K_{0.4}Fe_2As_2$	38	0.5	20	>100	200	>5.2

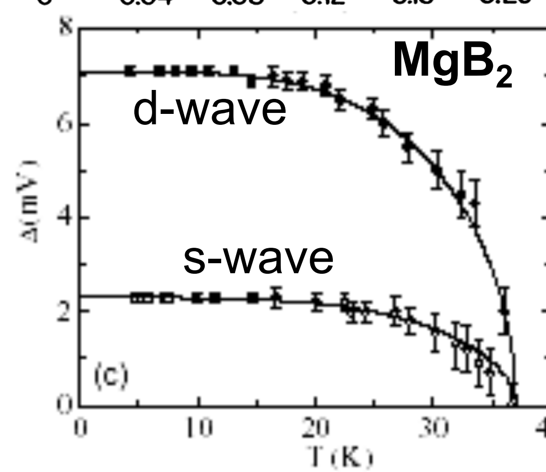
x 200

Courtesy of A.Gurevich



High-T_c d-wave cuprates are SRF unsuitable ($R_s \propto T^2$ instead of $R_s \propto \exp(-\Delta/T)$)

Large s-wave gap (good for SRF) is usually accompanied by low H_{c1} (bad for SRF)

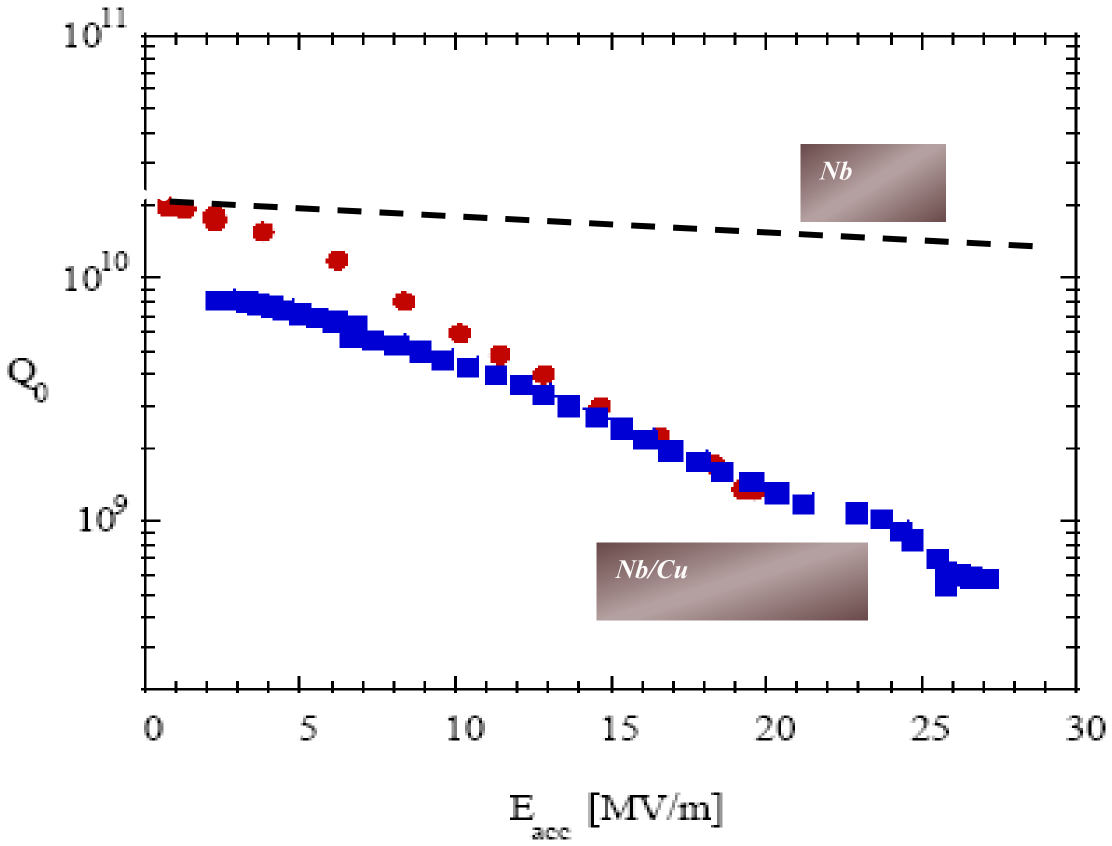


K.Saito IPAC2012 Talk

M. Iavarone *et al.*, PRL 89, 187004 (2002)

Thin Films: Niobium –State of The Art

1.5 GHz Nb/Cu cavities, sputtered w/ Kat 1.7 K (Q_0=295/R_s)



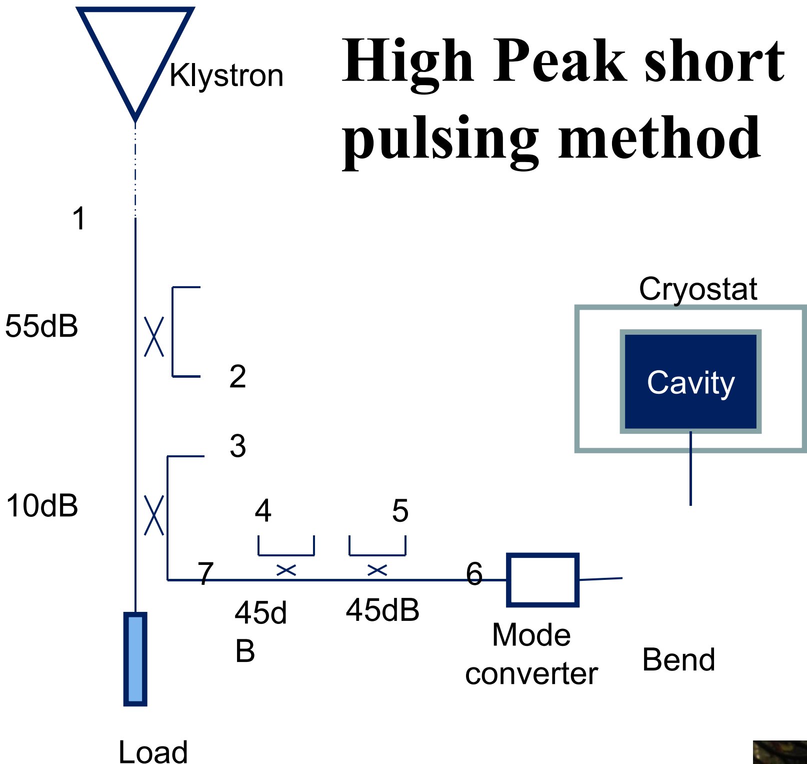
Bulk Nb like performance

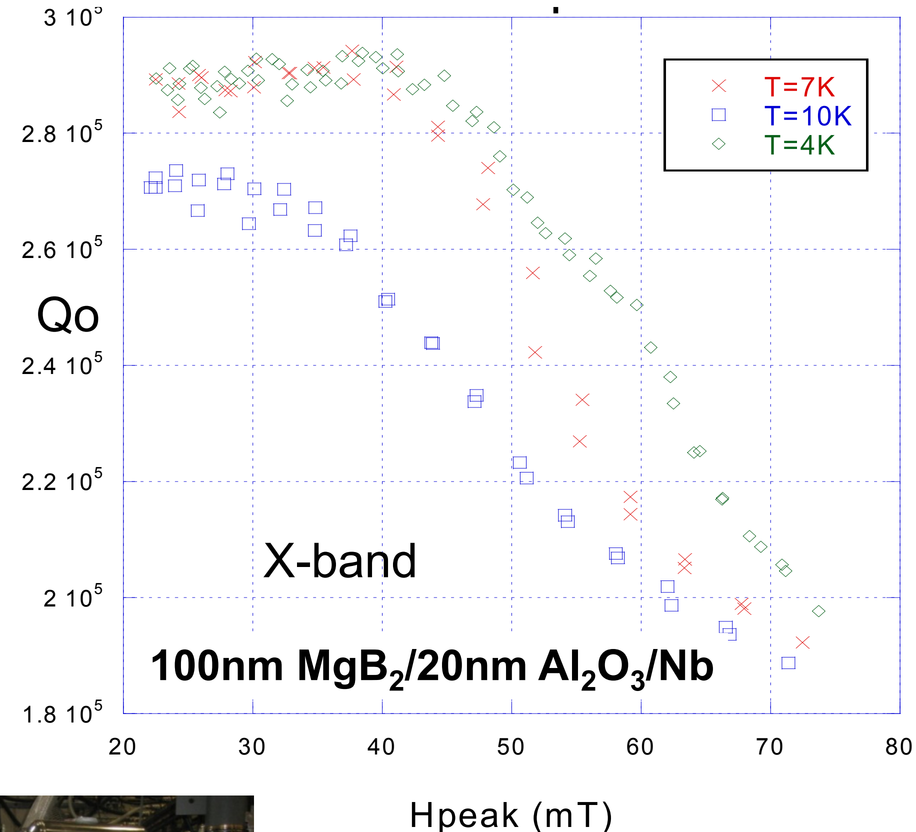
- Find best film coating technology
- Study the effect of substrate; Grain, Orientation, Preparation

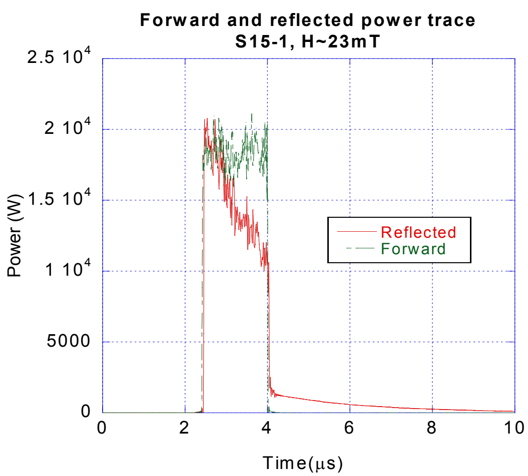
Courtesy of SLAC

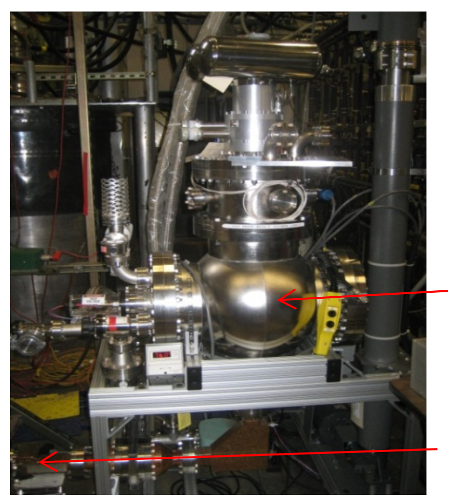
New Material Hunting

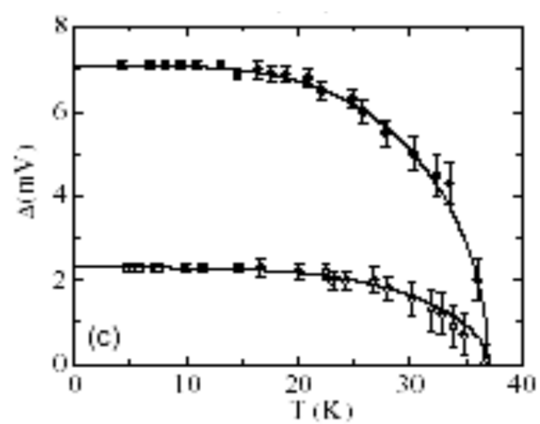
High Peak short pulsing method









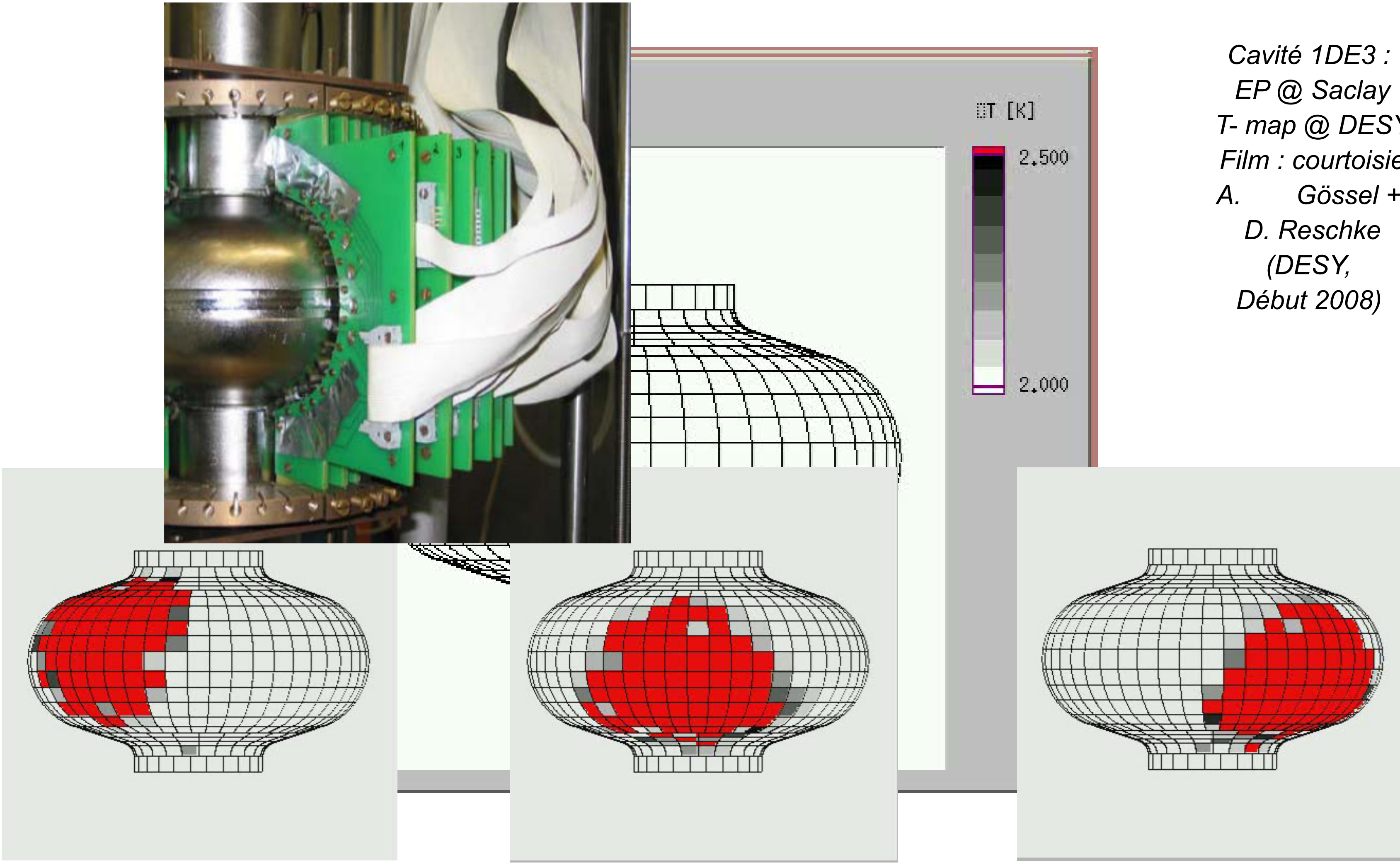


Summary

- The SRF performance of Nb bulk cavity has been very much improved in last two decades and is reaching the fundamental limit ~60MV/m.
- This state-of-the-art technology is based on the well understanding of performance limits and thanks to its suitable feedback to technology R&D;
  High Purity Nb material vendor production, Electropolishing, High pressure water rinsing, Ultrapure water, Cleanroom assembly, Baking, Hydrogen degas annealing and so on.
- Thin film multi-layer (TFML) coated cavity is proposed as the post niobium cavity for the gradient 100-200MV/m.
- MgB_2, NbN, Nb_3Sn are most candidate materials for TFML.
- Thin film coating technology has its specific issues learning from Nb film coated cavity, therefore TFML might not be straightforth to achieve the expected performance, it will take a time.
- High peak puls measurement method is very suitable for new material hunting. This method could make faster finding the new material.

Backup Slides

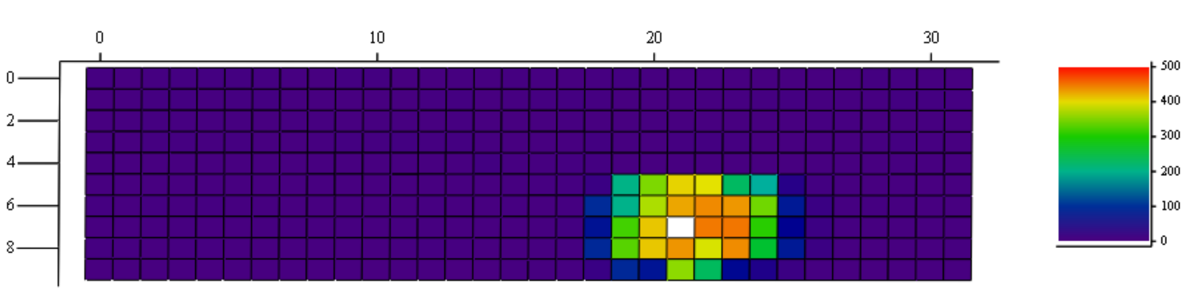
Bulk Nb ultimate limits : not far from here !

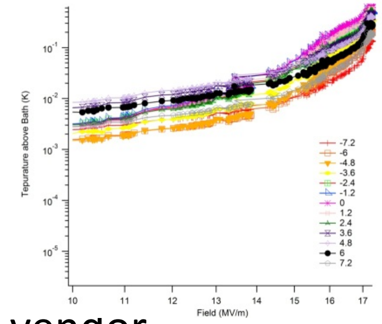


Cavité 1DE3 :
EP @ Saclay
T- map @ DESY
Film : courtoisie
A. Gössel +
D. Reschke
(DESY,
Début 2008)

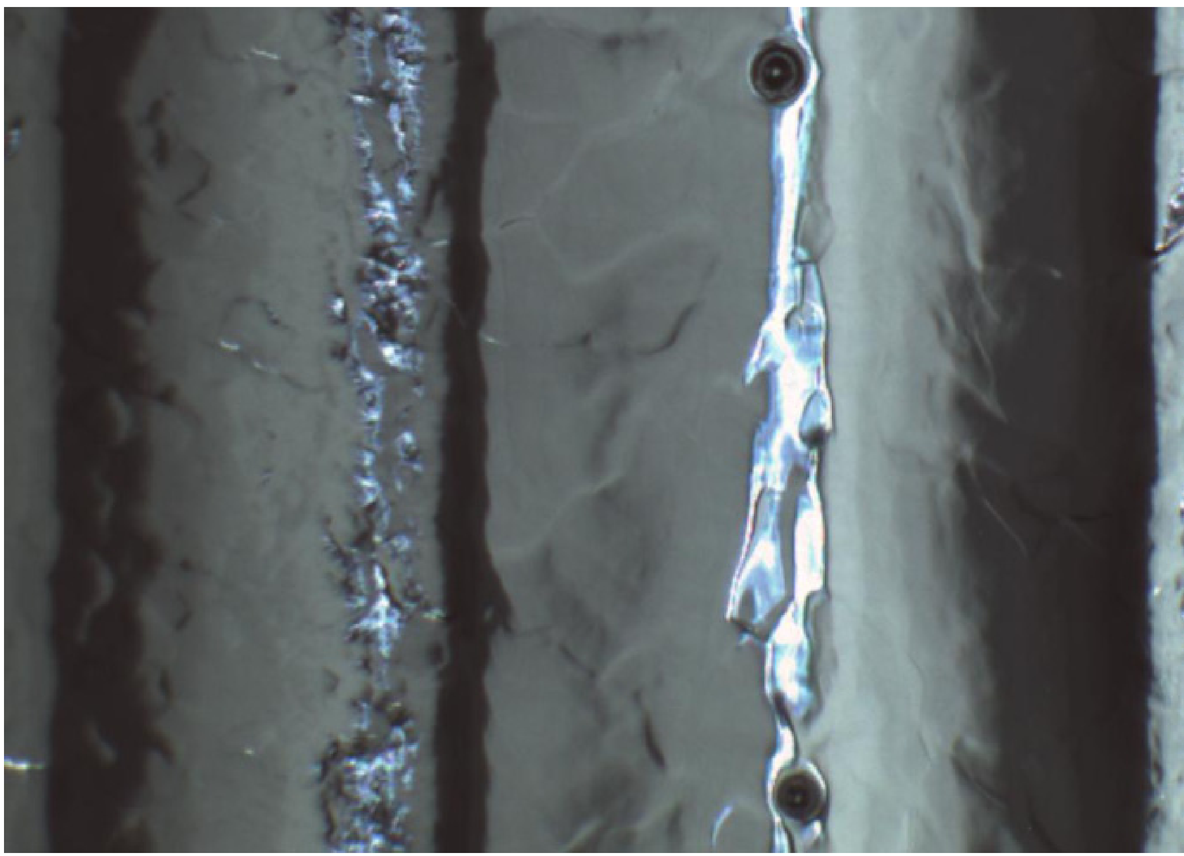
The hot spot is not localized : the material is ~ equivalent at each location
=> cavity not limited /local defect, but by material properties ?

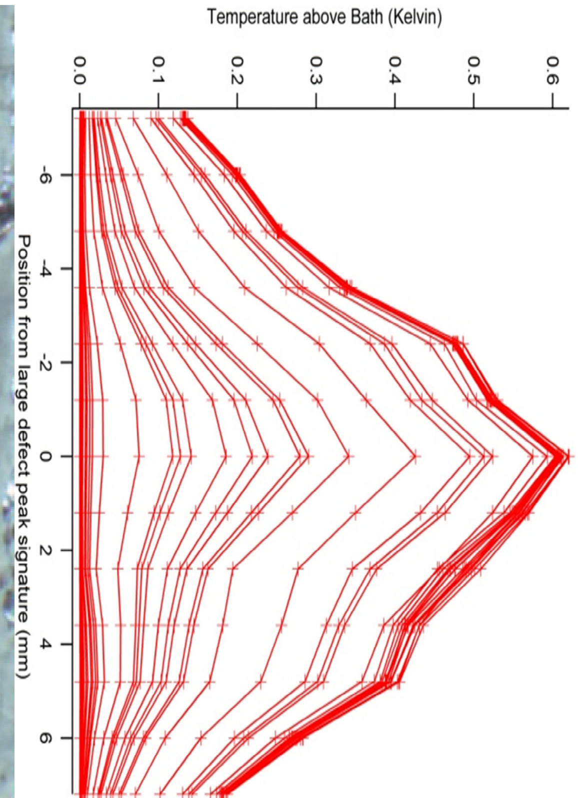
EBW defects limitig the gradient around 20MV/m



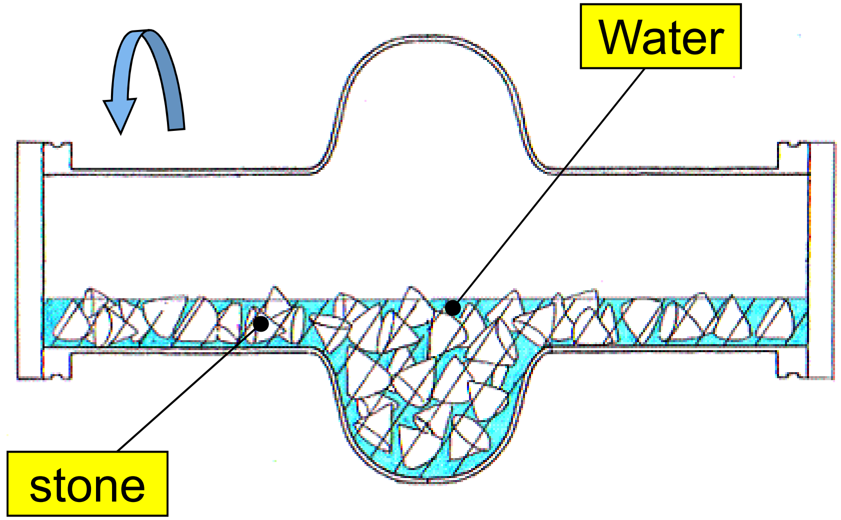


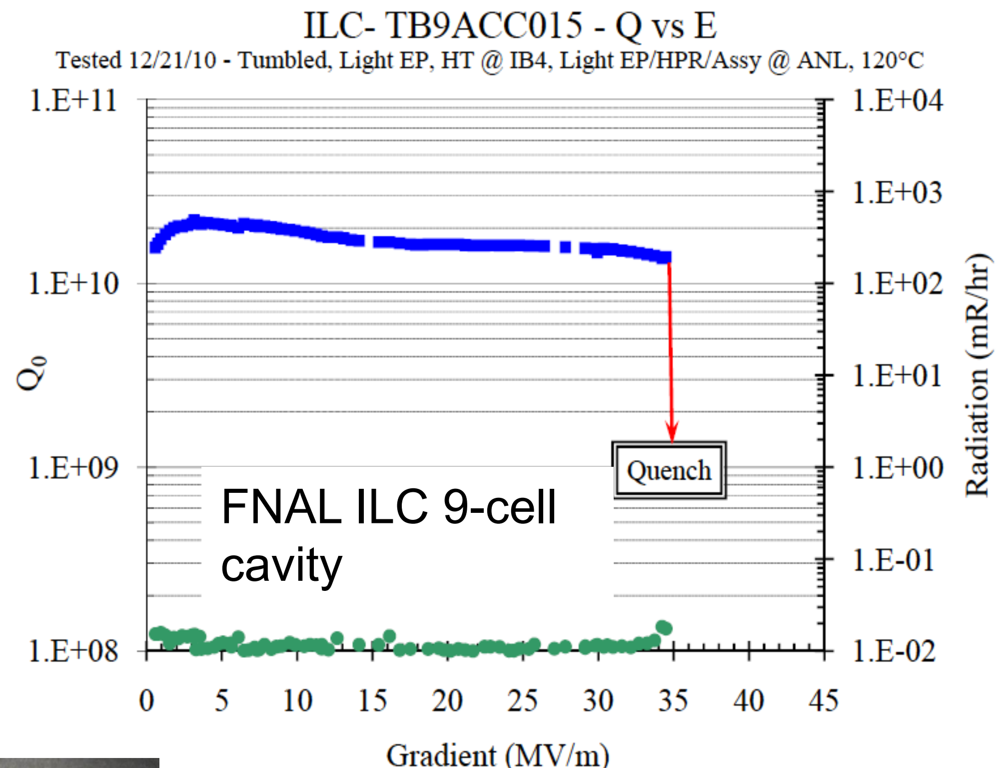
twin defects causing quench 17 MV/m. Cavity by a new vendor

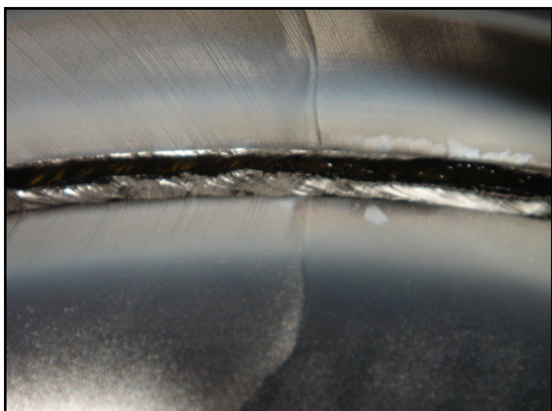




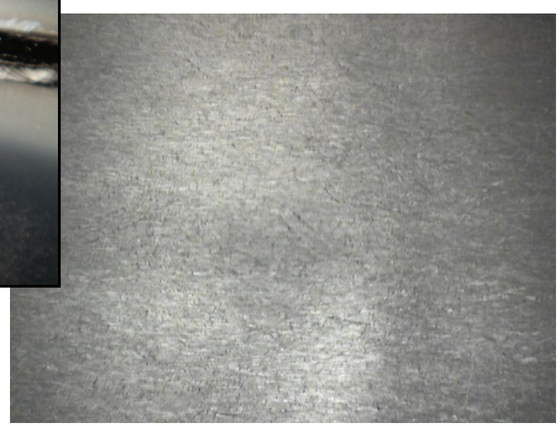
Defect Elimination byTumbling/CBP







Before CBP
(equator EBW seam)



After CBP

December 2010, FNALsucceeded the imprving gradient by CBP+Annealing+EP(40μm) from 18MV/m limit to 35MV/m