Fundamental RF Critical field Overview

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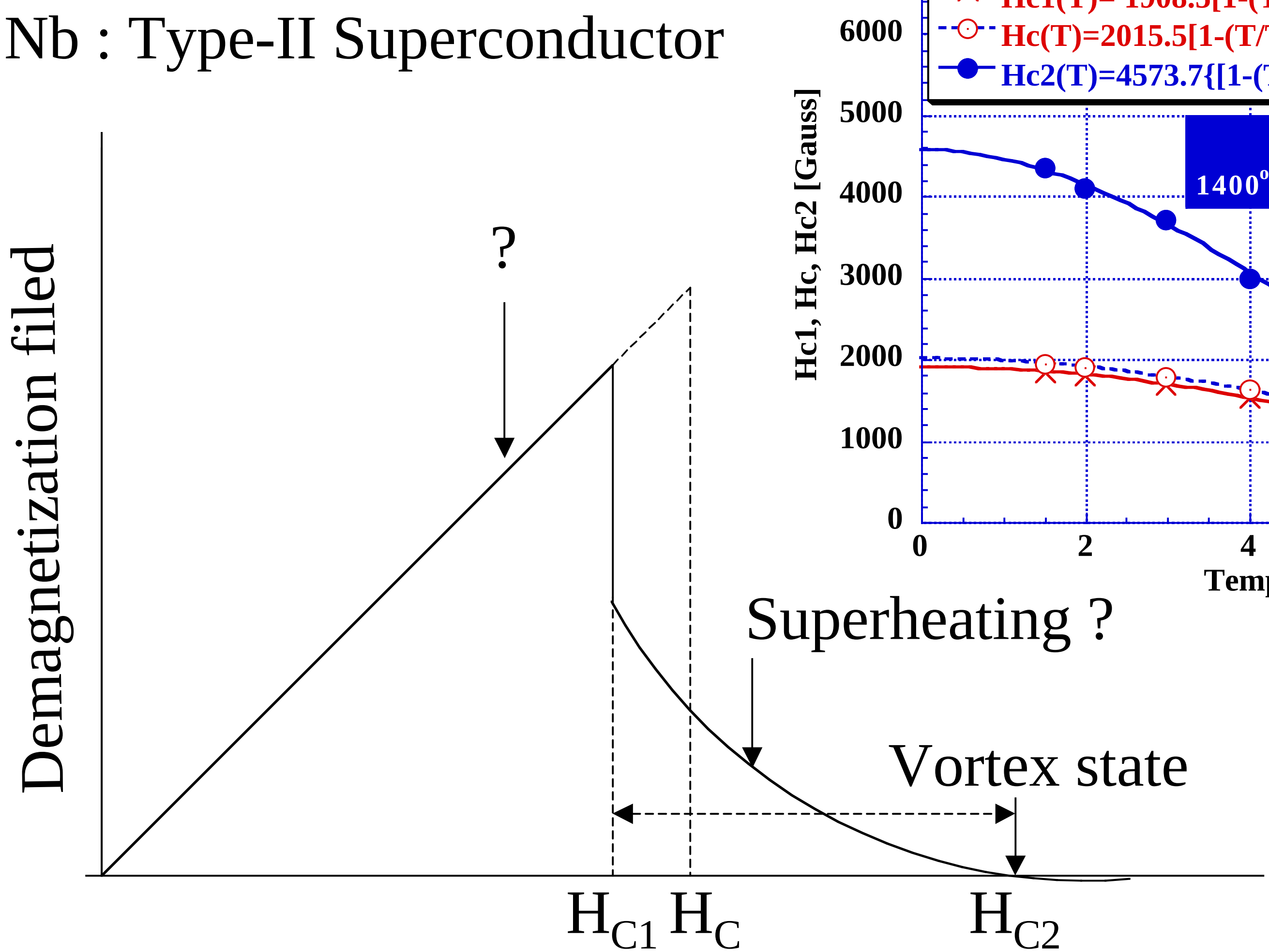
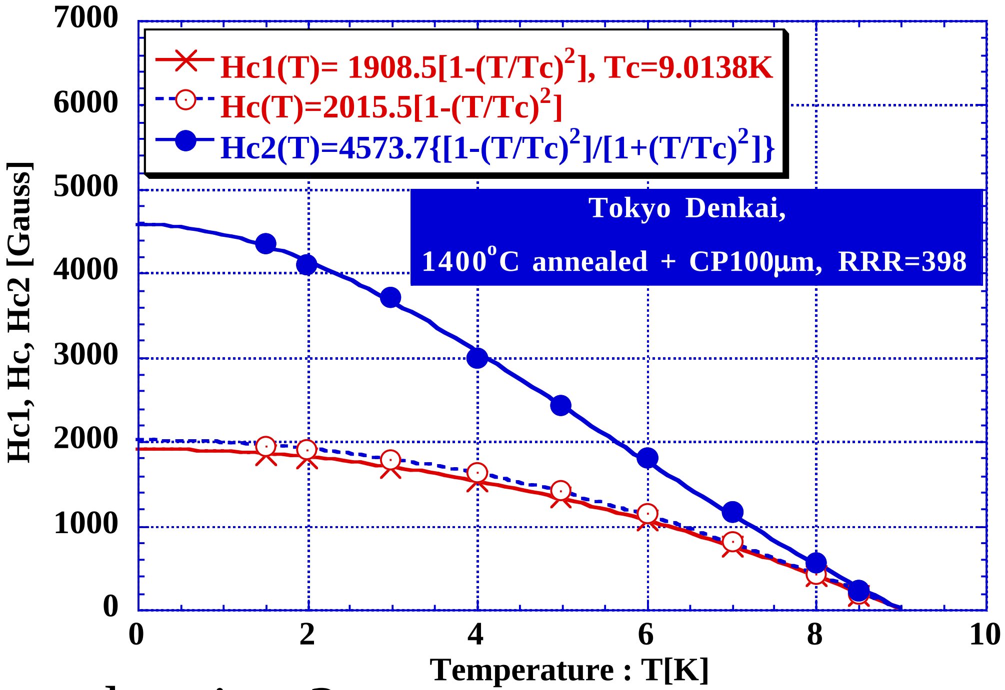
Outline

1. Overview
2. Theoretical Field Limits on SRF cavities
3. New Cavity Shape
4. Why EP has high gradient
5. Summary

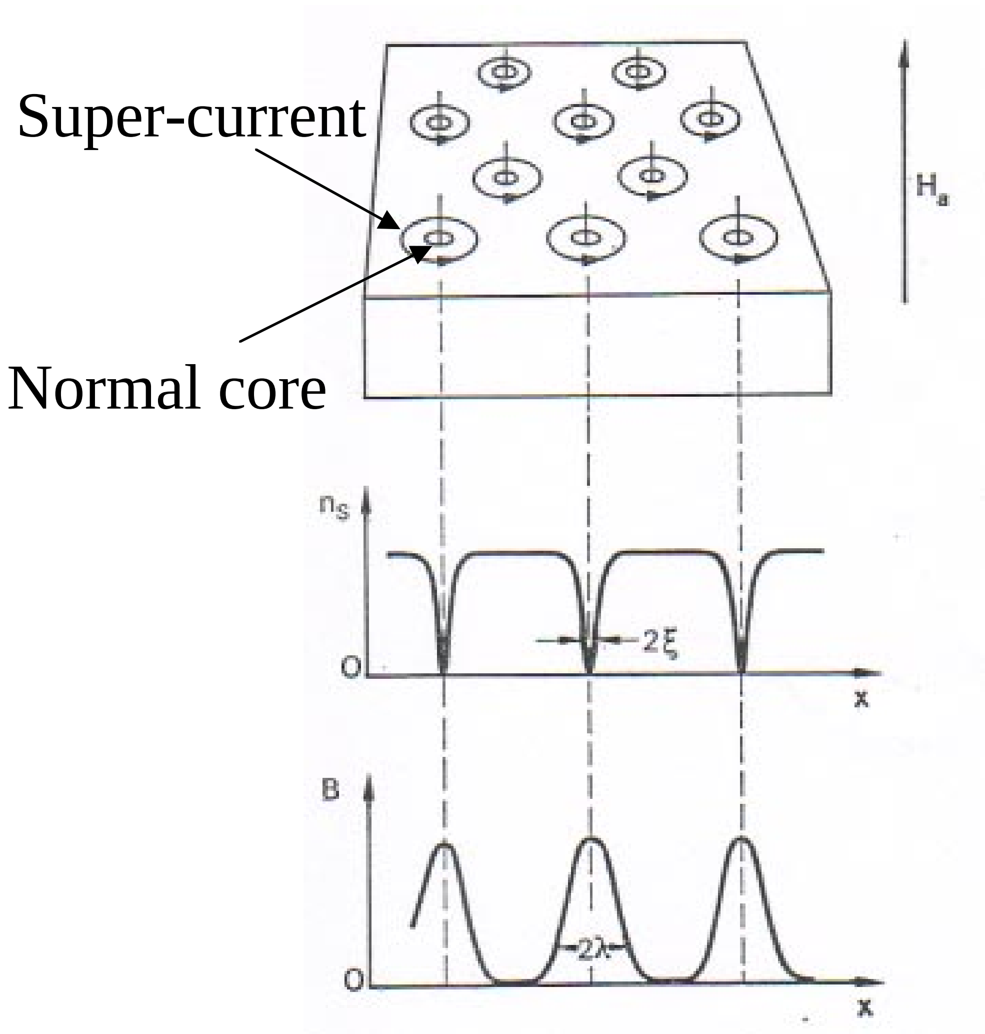
Possible Fundamental Limits

Nb SRF cavity will be limited by a theoretical limit but it is still open about by what.





Vortex State



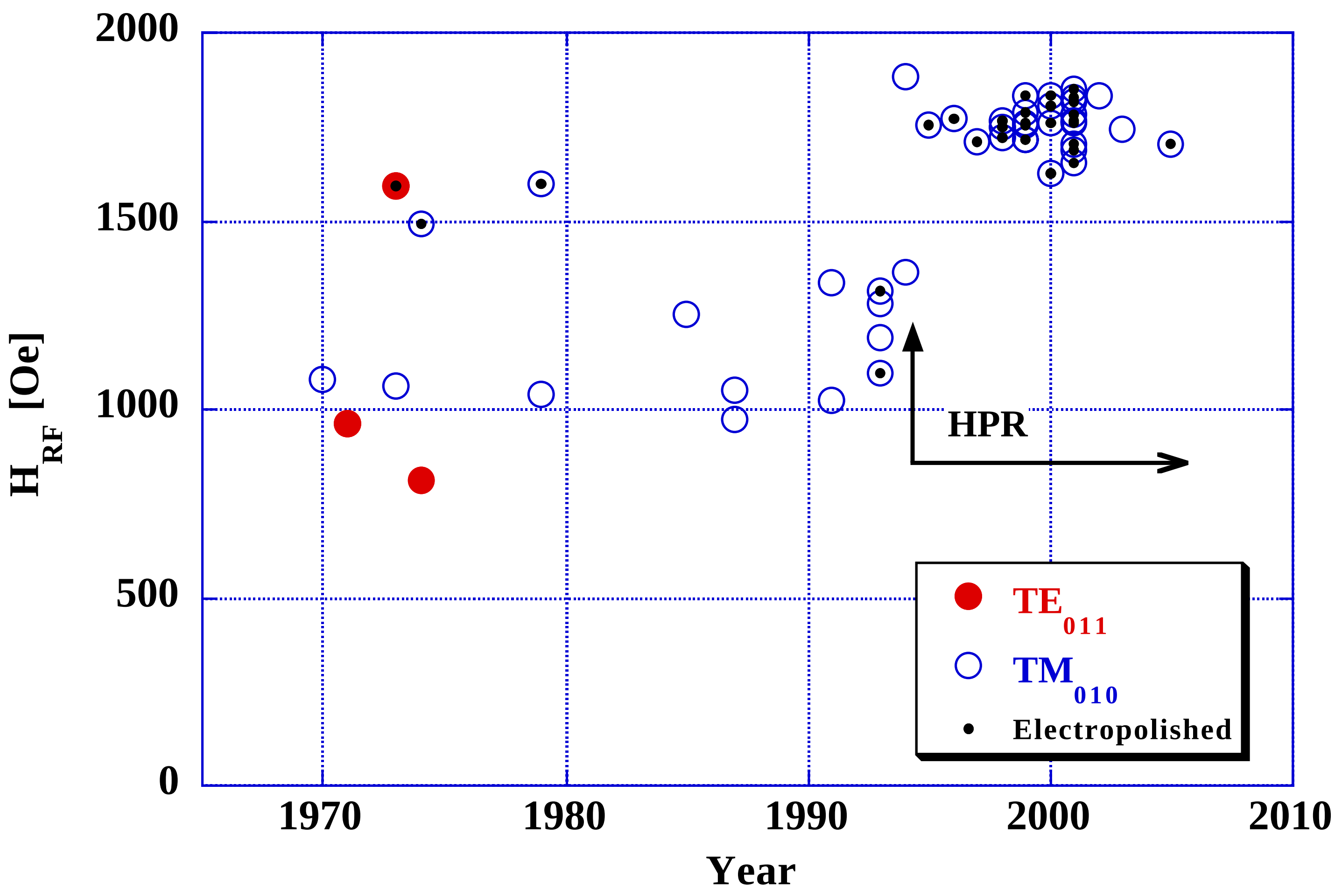
ξ: Coherence length

2ξ ~ Cooper pair size

λ: Field penetration length

2λ ~ size of normal core

Overview of the maximum RF field of Nb Cavity



1) **Rather high field had been reached already in the early stage by EP.**
2) **EP produces the high field more reliably than BCP.**
3) **The high field seems to be saturated to 1750 ± 100 Oe.**

High Gradient and Fundamental Field Limit

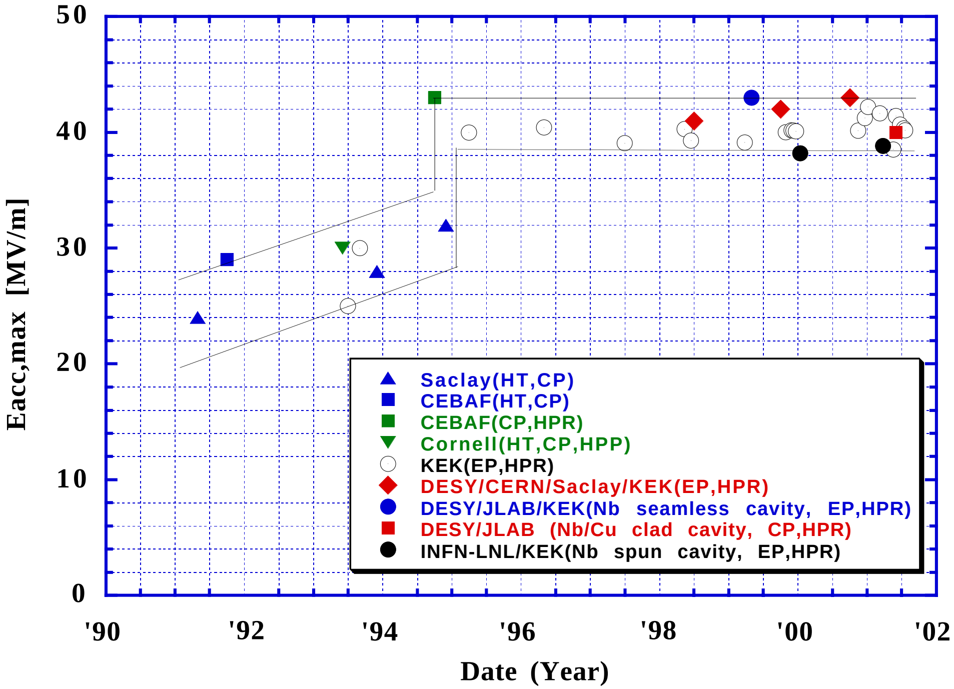


Fig.1 : History of High gradient n L-band Nb single cell cavities

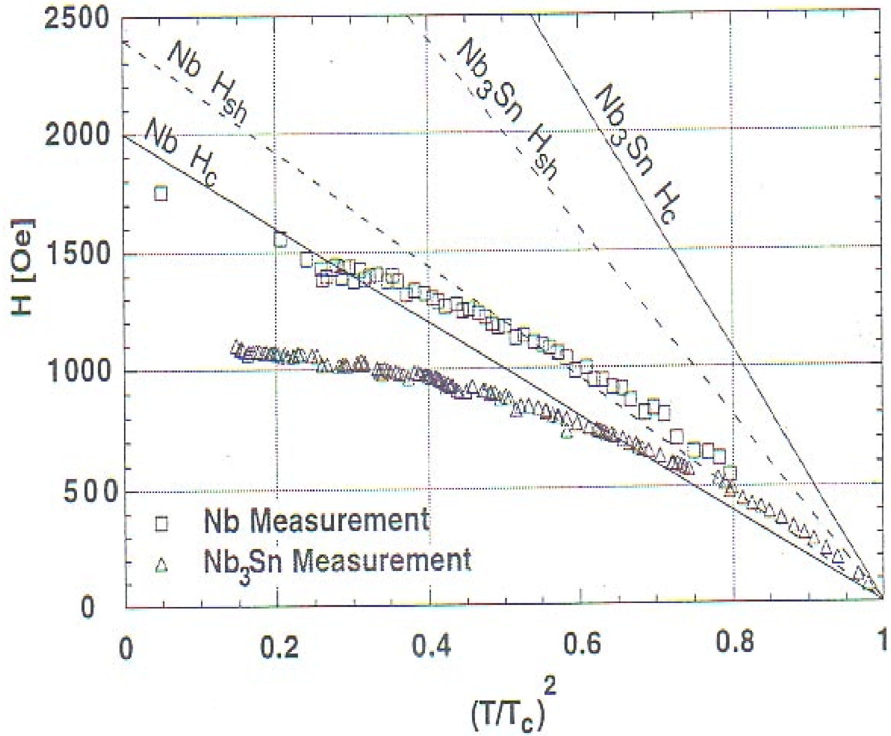
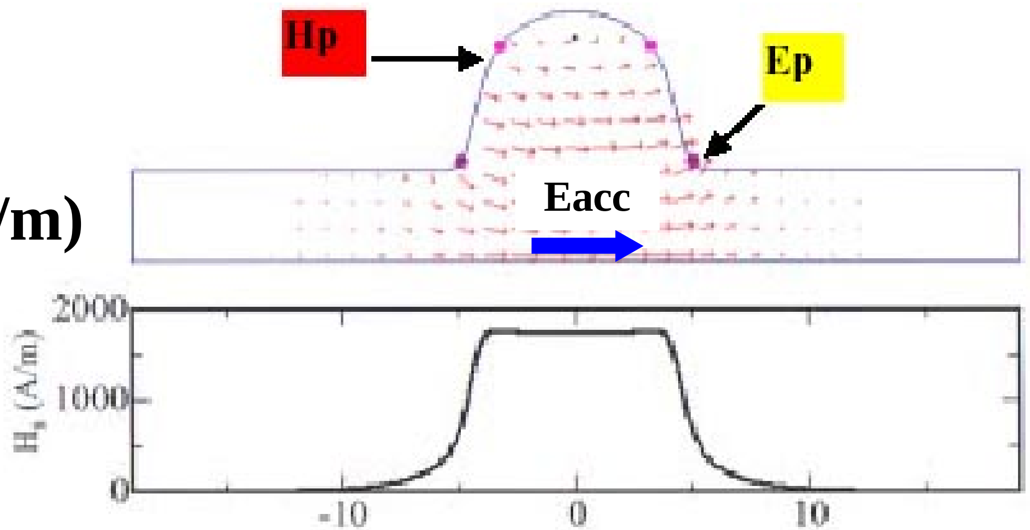


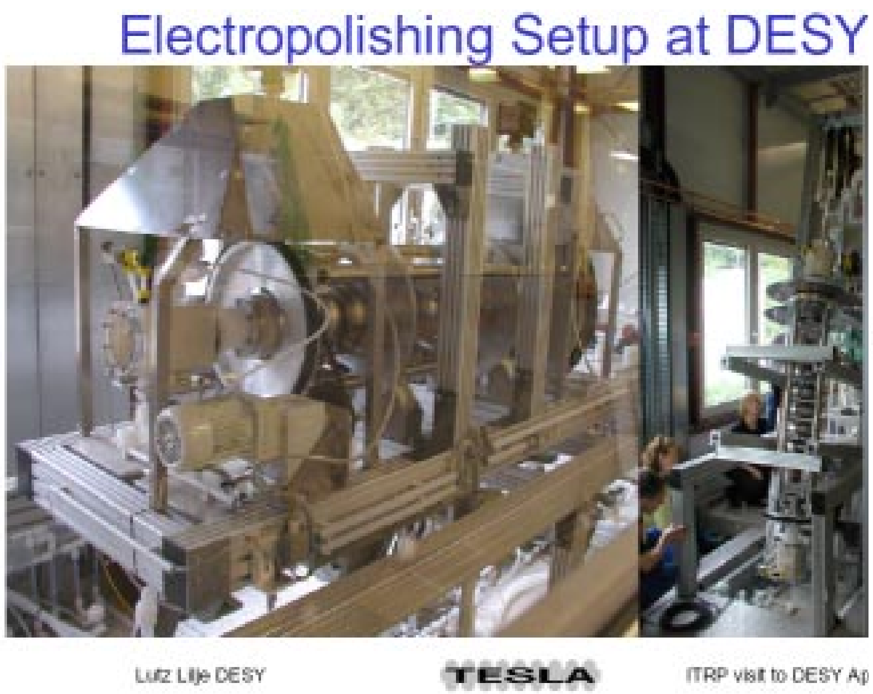
Fig.2 : Critical RF magnetic field by (Cornell U.)

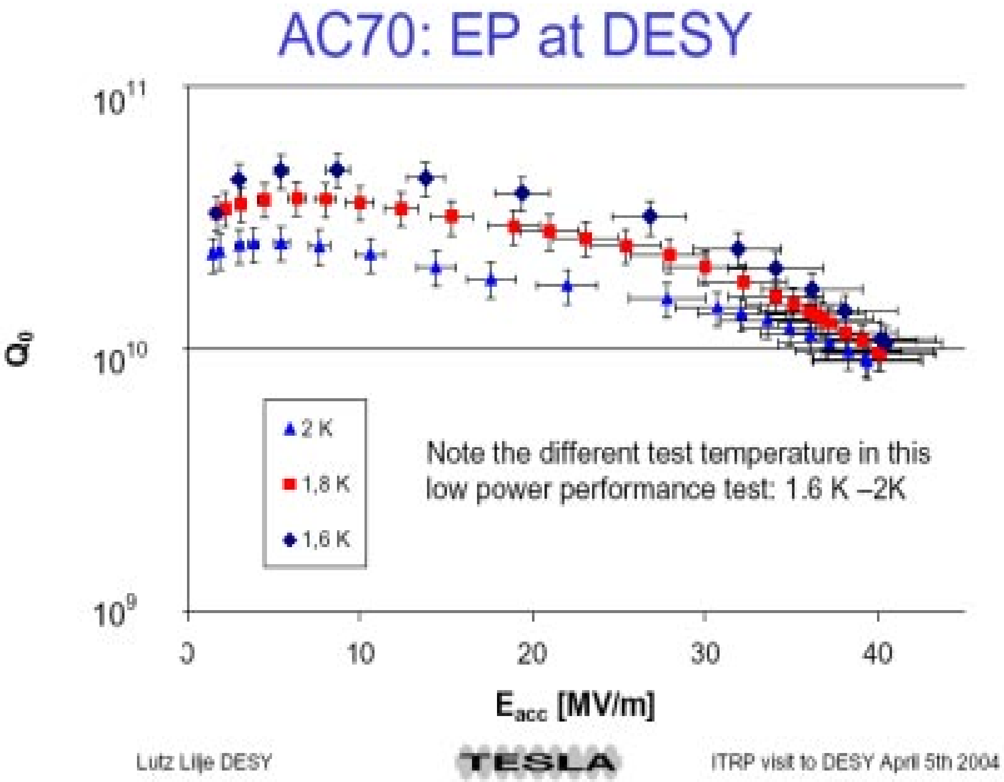
Hp/Eacc

~ 43 Oe/(MV/m)



40MV/m in a TTF 9-cell cavity





The field limitation of Hp ~1750 Oe with Nb cavity is no related to
1) cavity shape : beta =1 or beta =0.45,
2) fabrication methods : Nb seamless cavity, Nb/Cu clad cavity,
3) multi-cell structures : single cell or 9-cell.

Theories about the RF critical Field

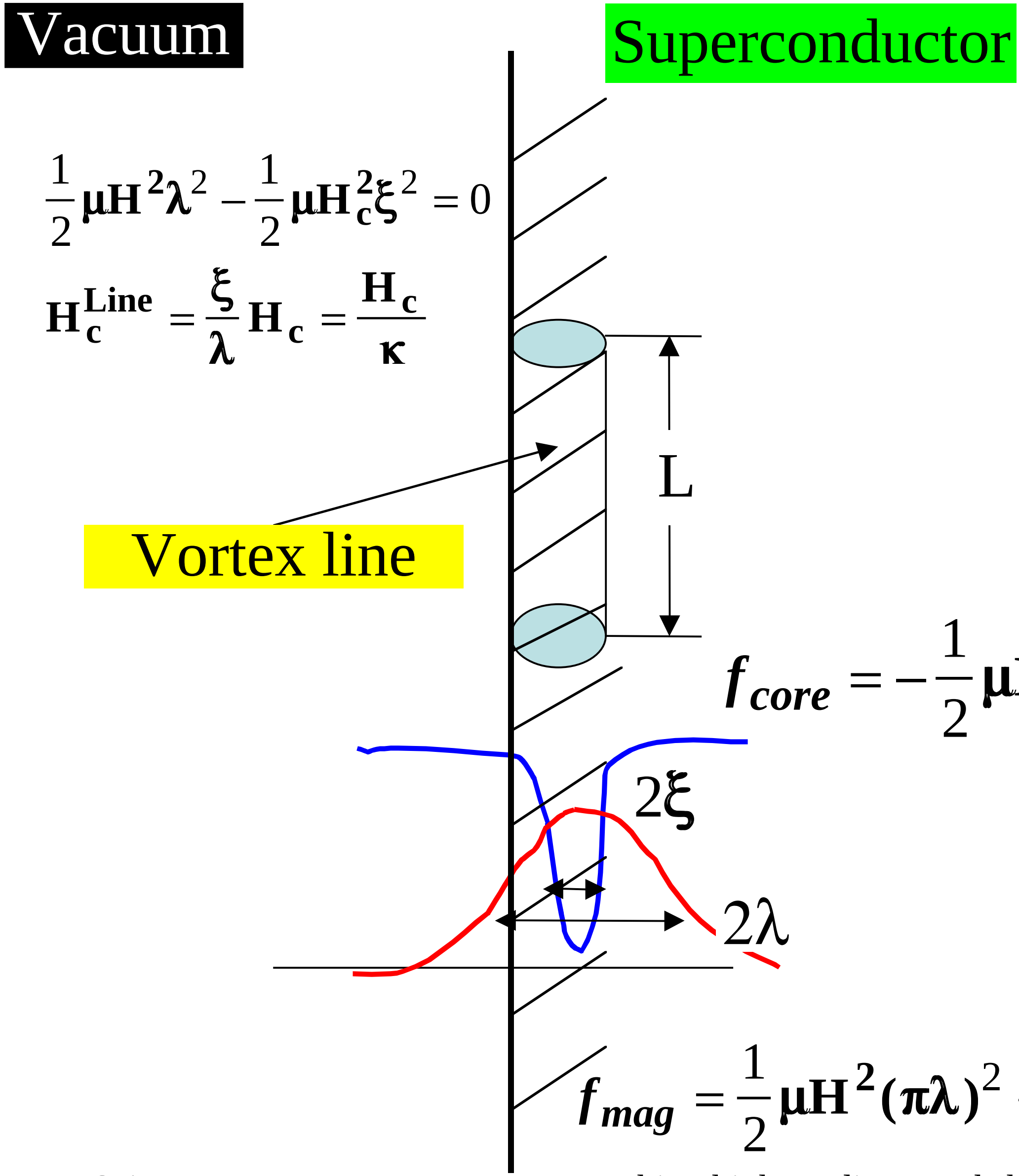
Model	Hmax [Oe] DC	AC	Availability
J.P.Burger and D.Saint-James (BSM)	Hc	Hc	κ >> 1
J.Maticon and D.Saint-James (MSM-I)	$\frac{1.29}{\kappa^{0.16}} \cdot \mathbf{H_c}$	$\frac{1.29}{\kappa^{0.16}} \cdot \mathbf{H_c}$	$\kappa > \frac{1}{\sqrt{2}}$
J.Maticon and D.Saint-James (MSM-II)	$\frac{0.89}{\sqrt{\kappa}} \cdot \mathbf{H_c}$	$\frac{0.89}{\sqrt{\kappa}} \cdot \mathbf{H_c}$	κ << 1
Orsay Group (OGM)	$\frac{\mathbf{H_c}}{\sqrt{\sqrt{2}\kappa}}$	$\frac{\mathbf{H_c}}{\sqrt{\sqrt{2}\kappa}}$	κ << 1
Vortex line nucleation (VLNM)	$\frac{\mathbf{H_c}}{\kappa}$	$\frac{\sqrt{2}}{\kappa} \cdot \mathbf{H_c}$	all κ
Vortex plan nucleation (VPNM)	$\frac{\mathbf{H_c}}{\sqrt{\kappa}}$	$\frac{\sqrt{2}}{\sqrt{\kappa}} \cdot \mathbf{H_c}$	$\kappa < \frac{1}{\sqrt{2}}$

κ: Ginzbrug-Landau parameter

$\kappa < \frac{1}{\sqrt{2}}$, type-I superconductor

$\kappa > \frac{1}{\sqrt{2}}$,type-II superconductor

Vortex line nucleation model (VLNM)



$$\frac{1}{2}\mu H^2\lambda^2 - \frac{1}{2}\mu H_c^2\xi^2 = 0$$

$$H_c^{Line} = \frac{\xi}{\lambda} H_c = \frac{H_c}{\kappa}$$

Effective field strength in AC application

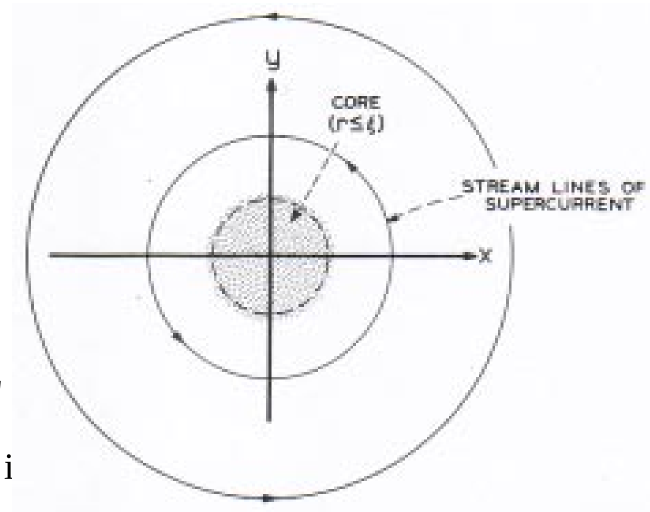
$$H_c^{Line}(T) = \frac{\xi(T)}{\lambda(T)} \cdot \sqrt{2} H_c(T)$$

$$= \frac{\sqrt{2} H_c(T)}{\kappa(T)}$$

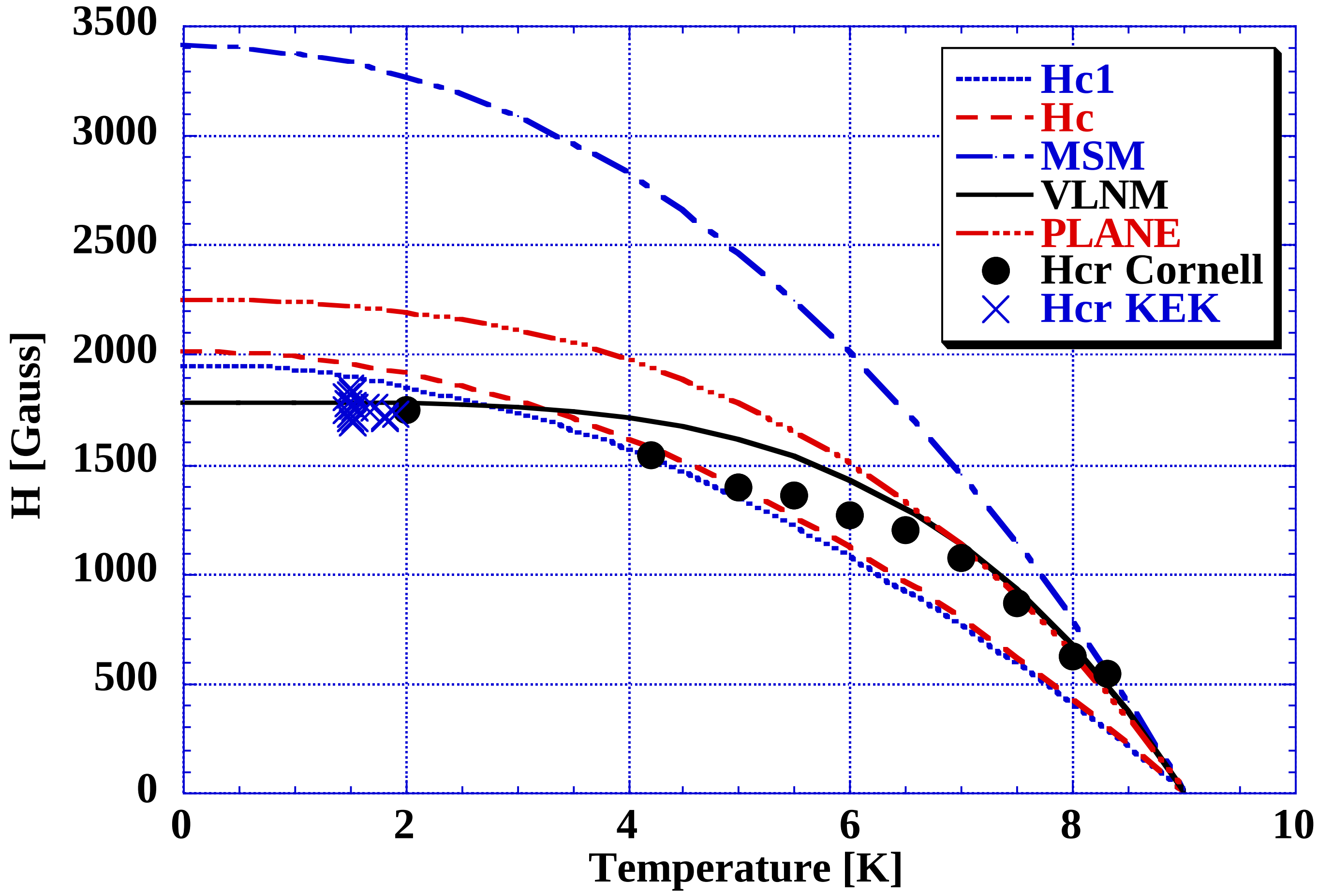
$$= \sqrt{2}\,\frac{H_c(0)}{\kappa(0)} \cdot \left[1 - \left(\frac{T}{T_c}\right)^4\right]$$

$$f_{core} = -\frac{1}{2}\mu H_c^2(\pi\xi^2) \cdot L$$

$$f_{mag} = \frac{1}{2}\mu H^2(\pi\lambda)^2 \cdot L$$

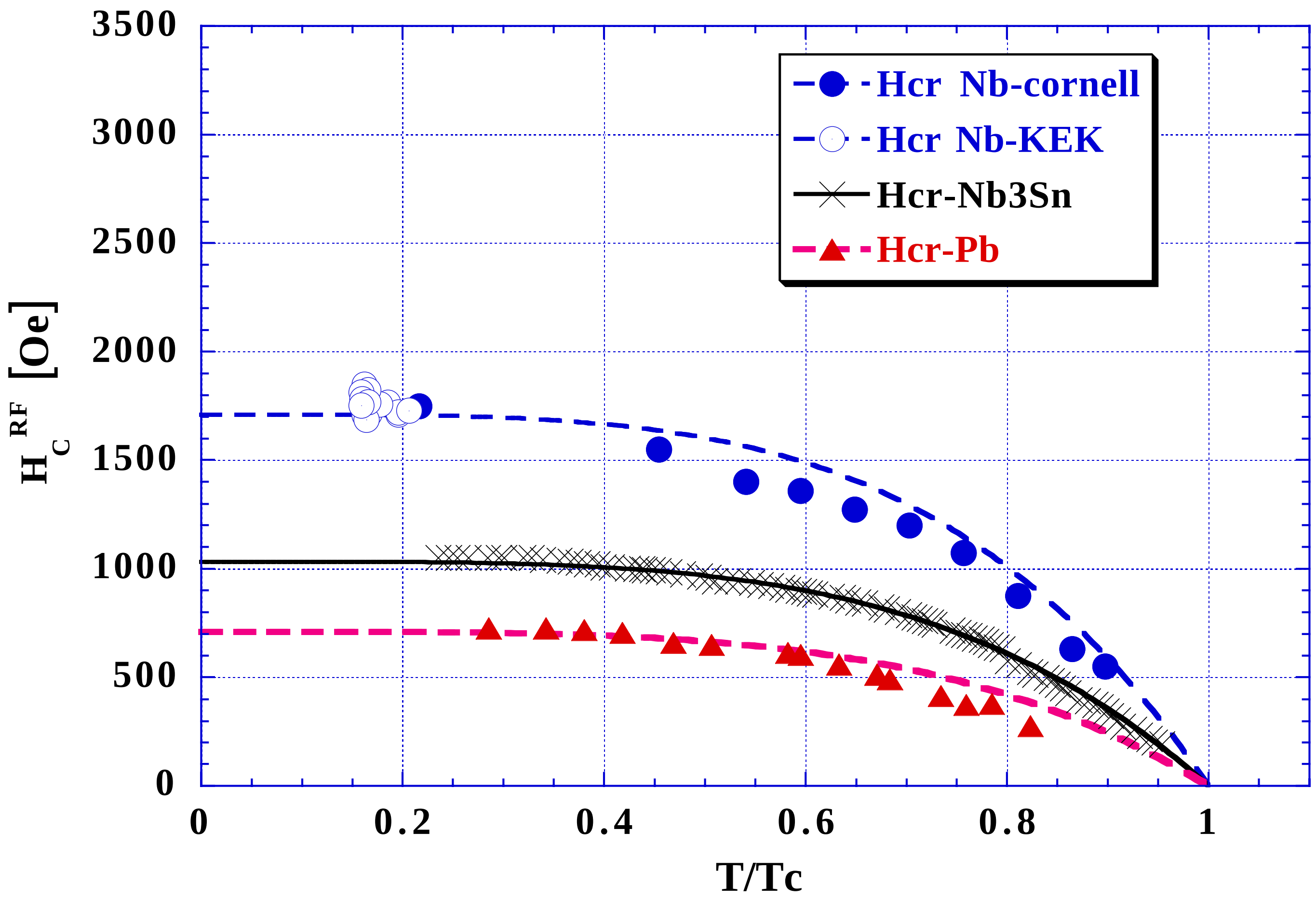


Comparison between Theories and Experiment Results



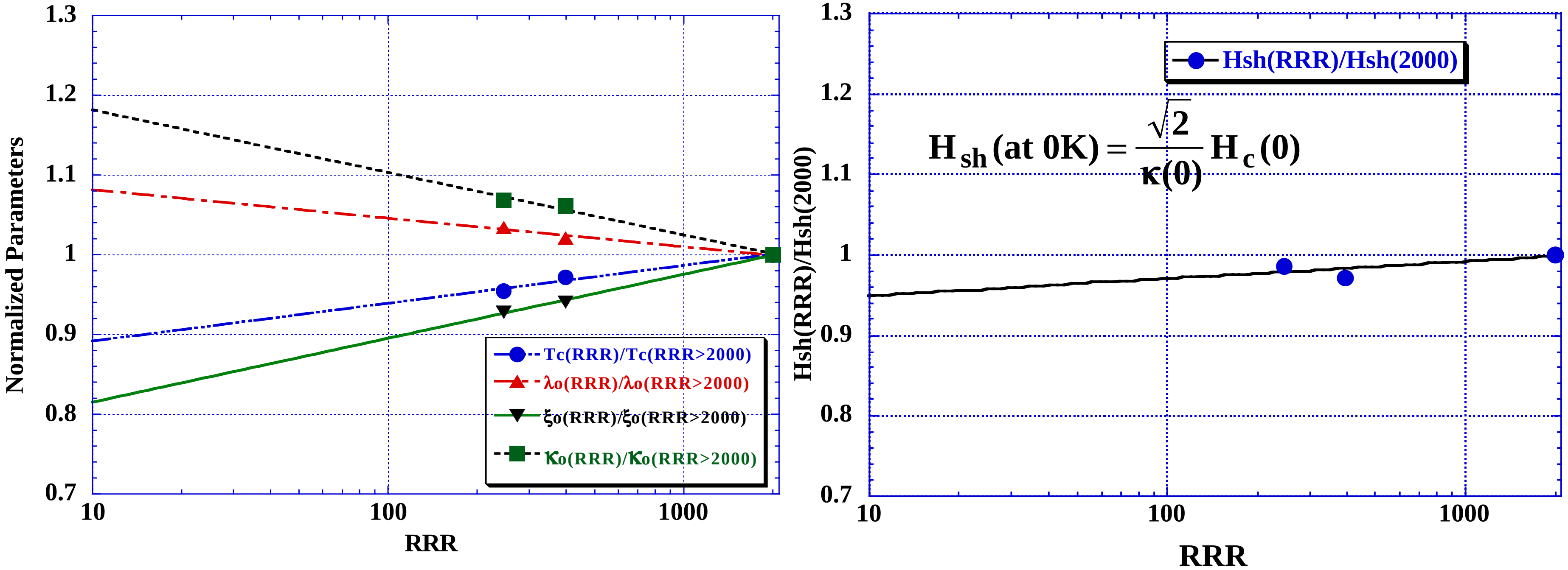
VLNM is the most promising model for Nb cavity.

Comparisons of VLNM with other materials



$$H_c^{Line}(T) = \frac{\xi(T)}{\lambda(T)} \cdot \sqrt{2} H_c(T) = \frac{\sqrt{2} H_c(T)}{\kappa(T)} = \sqrt{2}\,\frac{H_c(0)}{\kappa(0)} \cdot \left[1 - \left(\frac{T}{T_c} \right)^4 \right]$$

Less hope for the further material improvement



Only 5% improving is expected in

the ultra-pure niobium material (RRR=2000).

Cure for the high gradient : Eacc~50MV/m

Hp/Eacc depends on cavity shape !

For higher gradient,
smaller Hp/Eacc is essential.

Hp/Eacc ~ 35 Oe/(MV/m) for Eacc=50MV/m

$$\frac{1750}{50} = 35$$

e.g Pill box cavity without beam tube
Hp/Eacc = 30.5 Oe/(MV/m) , Eacc= 57.4 MV/m

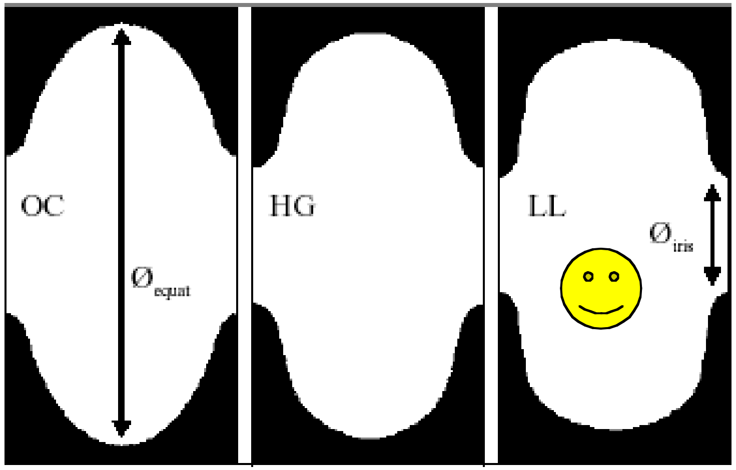


Figure 1: Geometry of three inner cells.

Table 1. Parameters of inner cells

Parameter		OC	HG	LL
$Ø_{equator}$	[mm]	187.0	180.5	174.0
$Ø_{iris}$	[mm]	70.0	61.4	53.0
k_{cc}	[%]	3.29	1.72	1.49
E_{peak}/E_{acc}	[-]	2.56	1.89	2.17
Hp/Eacc	[Oe/(MV/m)]	45.6	42.6	37.4
R/Q	[Ω]	96.5	111.9	128.8
G	[Ω]	273.8	265.5	280.3
R/Q·G	[Ω·Ω]	26422	29709	36103

byJ.Sekutowiczet al.

JLAB LL shape is expected 47MV/m as a realistic cavity shape.

Some problems with LL shape for 9-cell structure

The smaller bore diameter(53mm) makes several problems as follows:

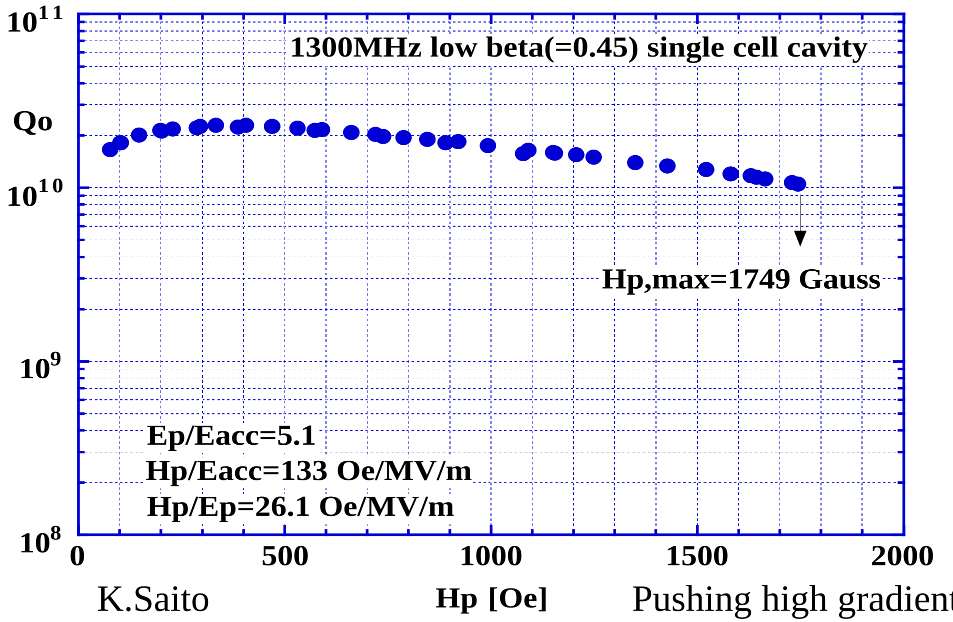
1) small cell-to-cell coupling ⟹ larger field error in each cell

$$\Delta Eacc \propto \frac{N_c^2}{\kappa_c} \cdot \Delta f$$

2) larger Ep/Eacc ratio(=2.17) related to the field emission problem

3) difficulty of inserting the cathode pipe in the cavity hole at electropolishing.

2) is no problem as long as EP use.



3) is also no problem ether.

EP needs the larger bore diameter than 60mm for1300MHz cavity.

When scaled 53mm(1500MHz) to 1300MHz, it is 61mm and no problem.

8-cell structure and Superstructure

If keep the same field error as the current TESLA 9-cell cavity, the number of cells is 8 as following:

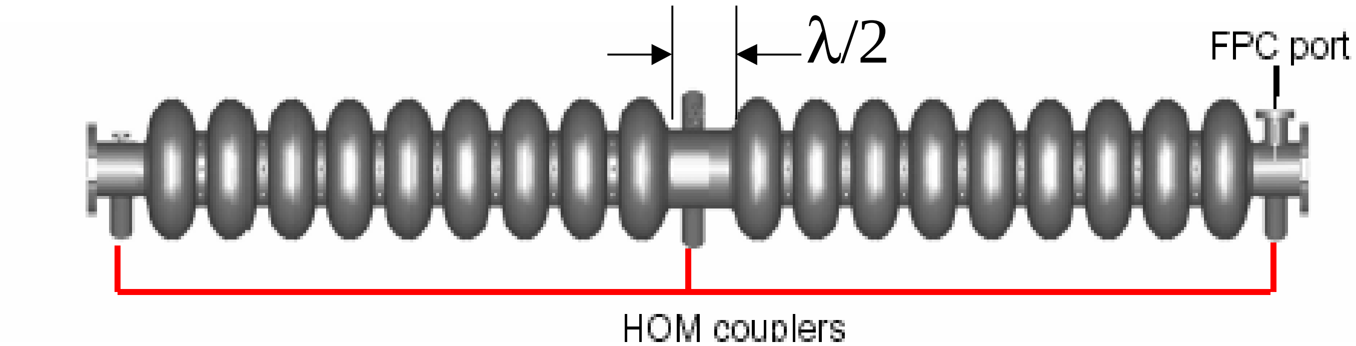
$$\frac{9^2}{1.87}\cdot\mathbf{\delta f} = \frac{\mathbf{N_c^2}}{\mathbf{1.49}}\cdot\mathbf{\delta f} \Rightarrow \mathbf{N_c} = 9\cdot\sqrt{\frac{1.49}{1.87}} = 8.03 \cong 8$$

However, the shorter structure losses the fill factor and resulted in lower energy reach.

2 x 8-cell superstructure can solve this problem.

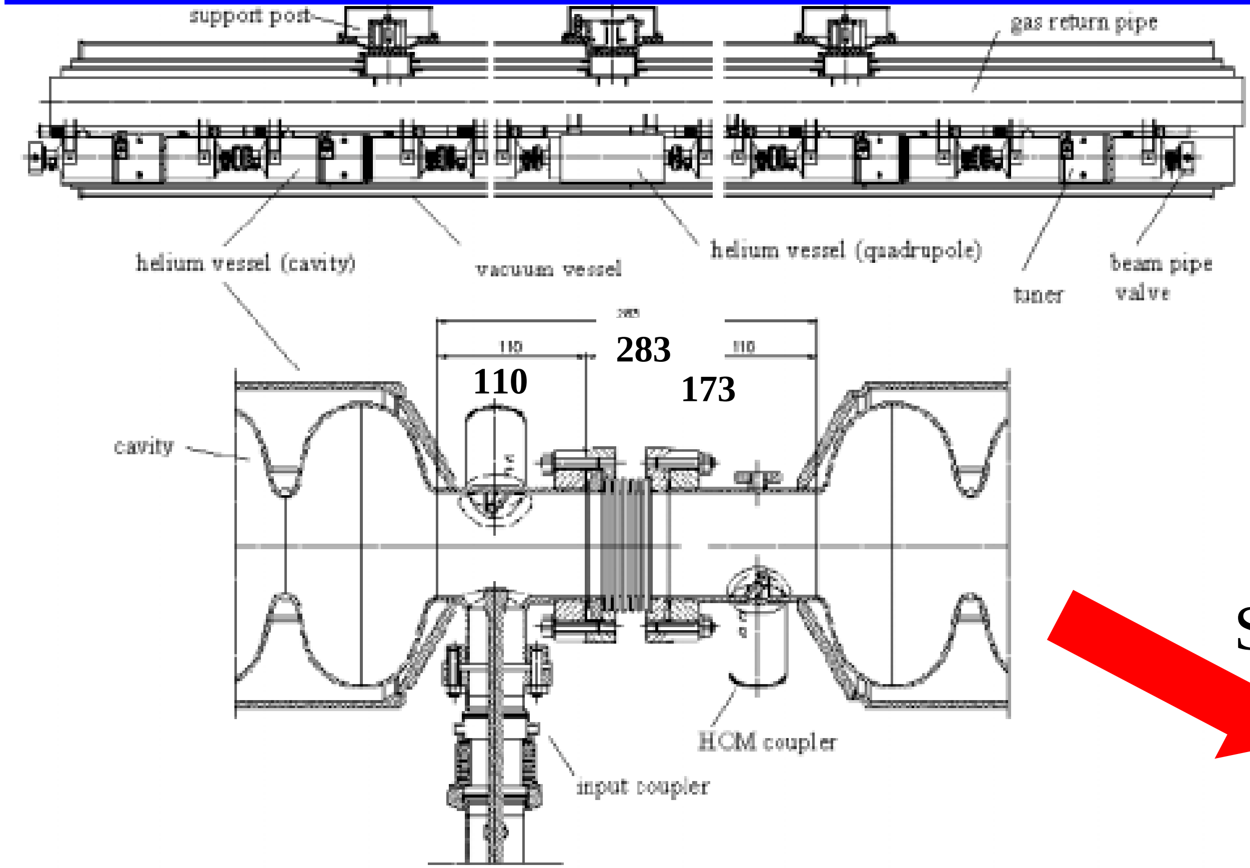
Example:

In a 18-cell structure, field error is serious by a factor 4 than a 9-cell. However, if one connects the two 9-cell structure through one beam pipe of a λ/2 wave length, the problem is reduced much.



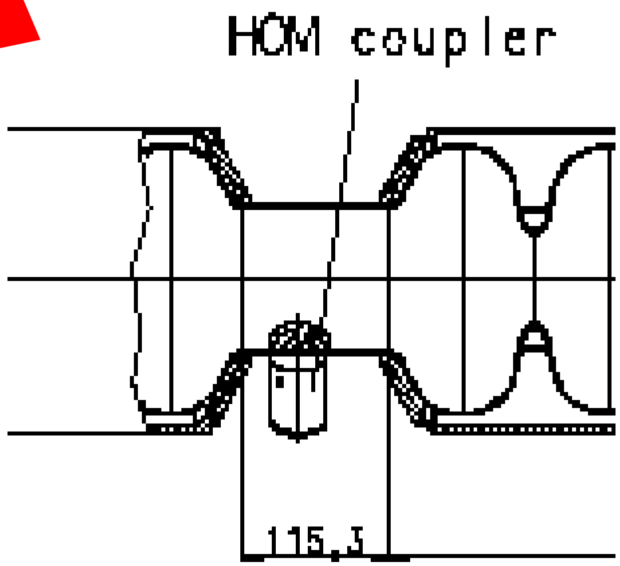
2x9-cell superstructure proposed for the TESLA800

2 x 8-cell superstructure



Merits of SST
1) Improved the fill factor
2) Less input coupler

Superstructure



17m Cryomodule	12 x 9-cell TESLA	7 - 2 x 8-cell SST
Total cavity length [mm]	15785.4	15638.7, shorter by 146.7
Total number of cells	98	112
Fill factor: $\frac{\text{Total cell length}}{\text{Total cavity length}} \times 100$	78.9 %	82.6%

The proposed 1-TeV ILCs

Energy Reach [GeV]	Gradient [MV/m]	Main LINAC effective length [km]	Main LINAC total length [km]	Tunnel length [km]
TESLA500 (510) (1752 17m cryomodules)	23.4	21.8	29.78	33
TESLA800 (810) (1596 17.6m cryomodules)	35.0 2 x 9-cell SST	25.45	28.09	33
US SCLC 500 (510) (1462 17m cryomodule)	28.0	18.22	24.85	46.8
US SCLC1000(1020) (2340 17m cryomodules)	35.0	28.590	39.78	46.8
SCLC500 (510) (1170 17m cryomodules)	35.0	14.58	19.89	33
SCLC1000(1018) (1752 17m cryomodules)	45.0 2 x 8-cell SST	22.64	29.53	33

Why EP produces high gradient

- The SRF critical field is 1750±100 Oe on niobium.
- BCP etches the grain boundary steps especially on the EBW seam and results in the field enhancements about a factor 2 due to the steeper steps.

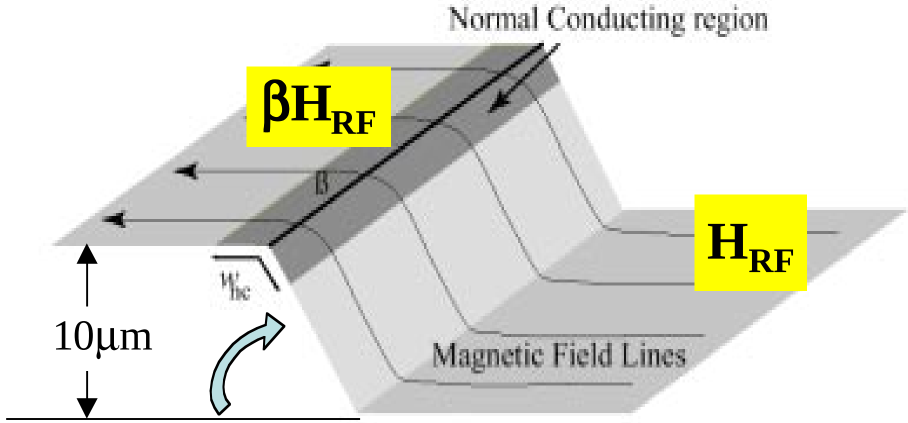
  Q-slope starts from about 20MV/m and limits the high gradients.
- On the other hand, EP has less boundary etching and the surface is smooth enough against the field enhancement. Thus, 40MV/m high gradient is reached in the present cavity shape with Hp/Eacc ~ 43 Oe/(MV/m).

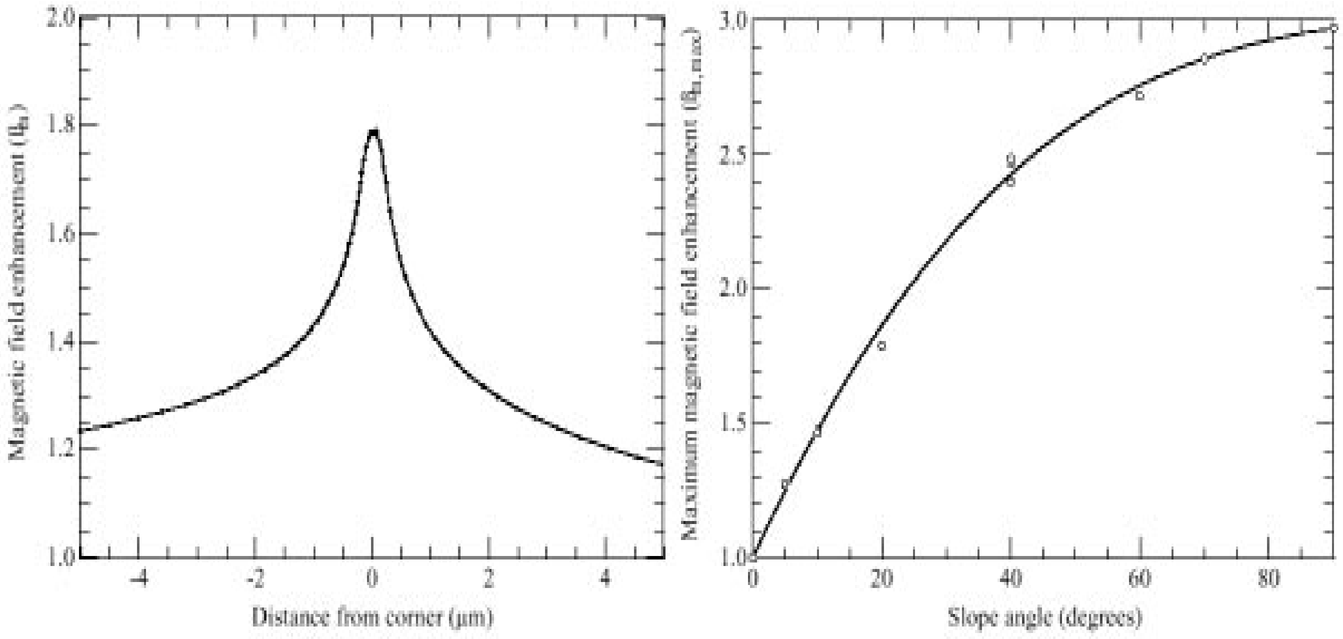
SRF magnetic field enhancement on the steeper grain boundary steps

By J. Knobloch

Es ⟶ βEs

Z=E/H Hs ⟶ βHs



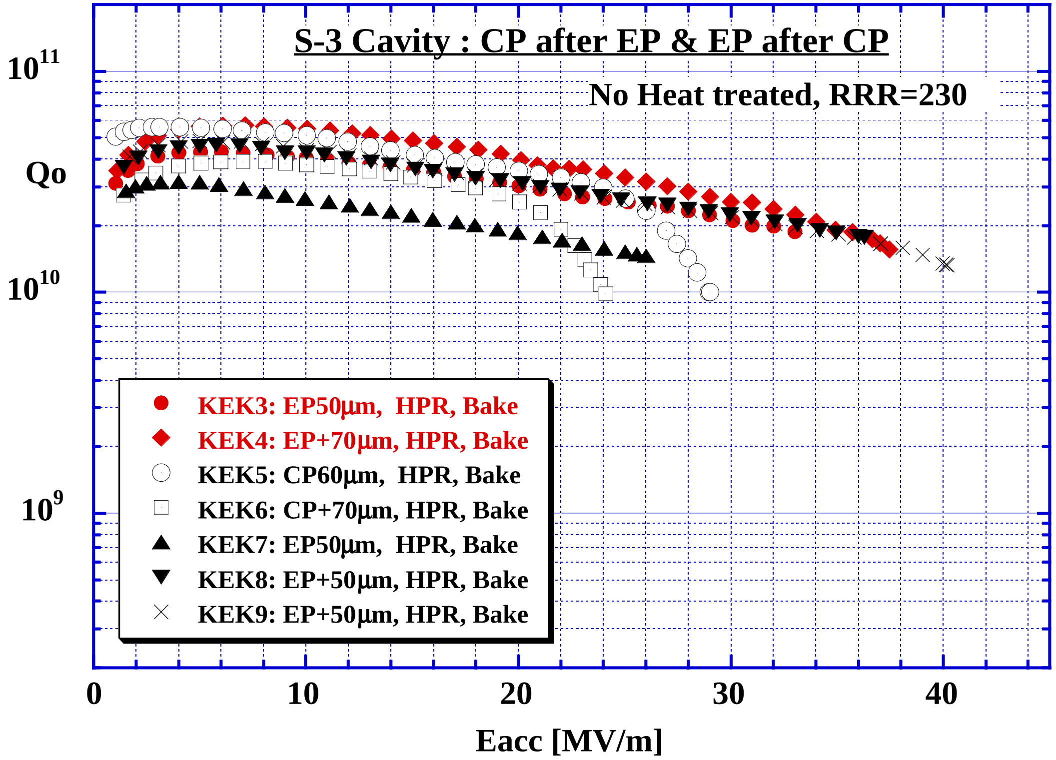


(a) (b)

Experimental evidence -I

CP after EP and EP after the CP

By E.Kako

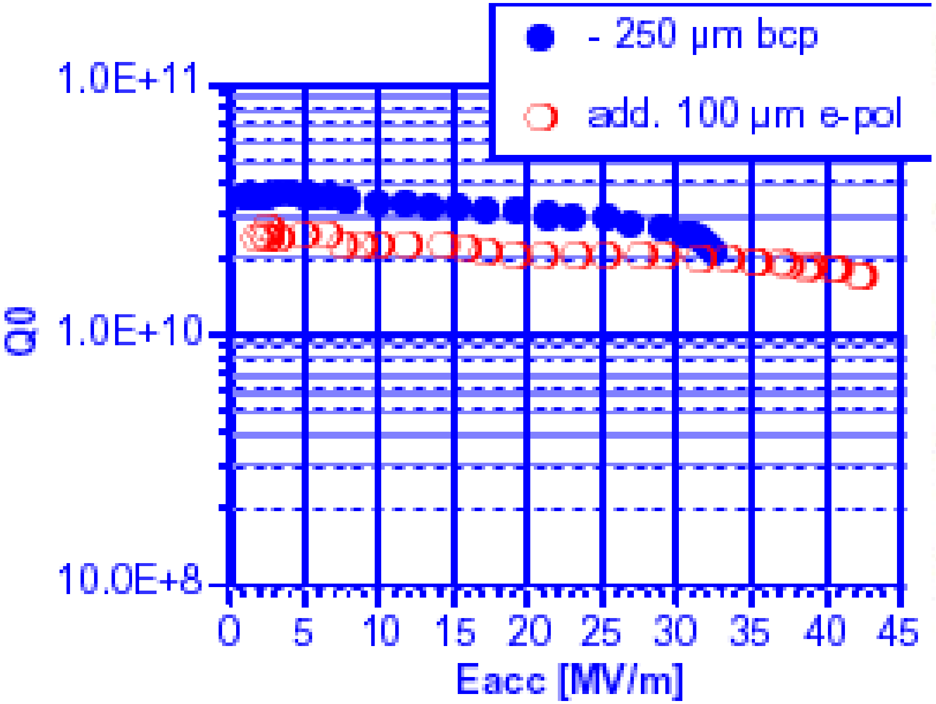


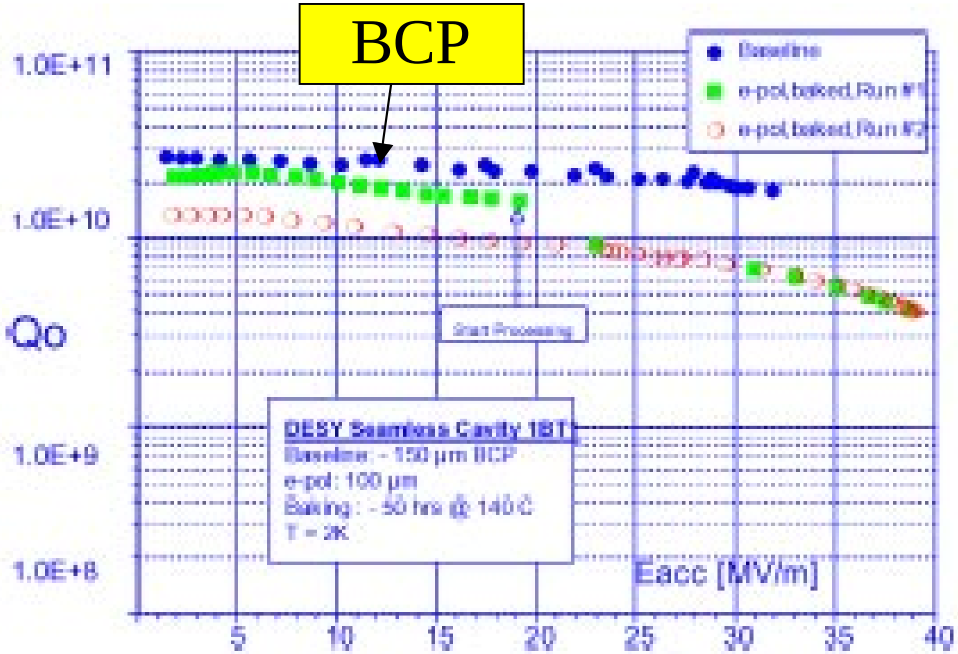
EP upgraded high gradients to 39MV/m,
then CP degraded 29MV/m by 60µm and 24MV/m by following 70µm,
the following EP upgraded to 40MV/m.

Experimental evidence - II

Seamless Nb bulk cavities (no EBW seam on equator) more likely have less Q-slope.

By W.Singer, P.Kneisel



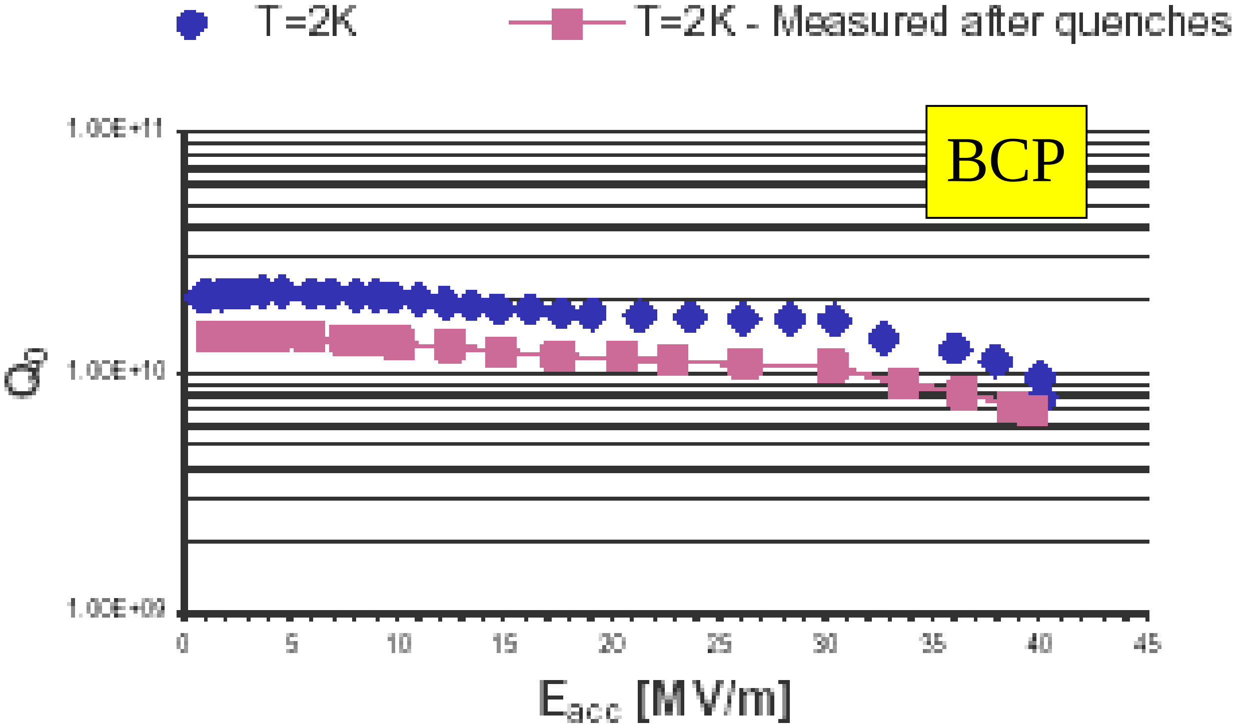


Experimental evidence - III

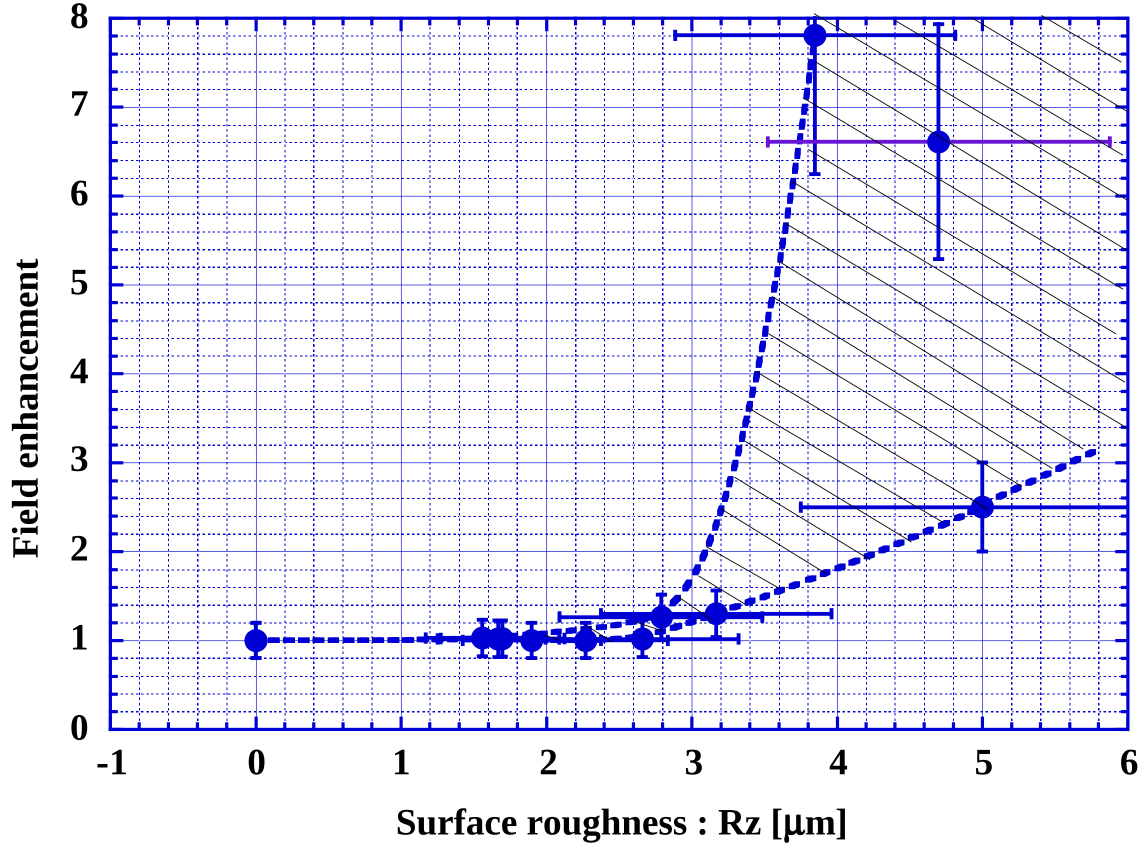
Nb/Cu clad seamless cavity

No EBW seam and better cooling

By P.Kneisel



What roughness needs for high gradient



Surface roughness should be smaller than 2µm against the field enhancement effect.

Unexplainable Results

- Above my theory dose not explain the two results:

  P.Kneisel's 43MV/m by BCP on Nb welded cavity ,

  B.Vissentin's 40MV/m by BCP on Nb welded cavity.

  This is my headache for a long time.

- Still something is missed.

Summaries

- The field gradient of SRF cavities are more likely limited by critical RF magnetic field due to vortex line nucleation.
- Niobium cavity is limited around Eacc=40MV/m with present TESLA cavity shape by the theoretical limitation. If one applies new shape like JLAB's LL shape, nearly 50MV/m is expected.
- The high gradient performance on EP is related to the field enhancement phenomena.