S. Calatroni, F. Gerigk, W. Weingarten

SC cavities: performance as a function of frequency and temperature

Outline

- Choice of accelerating gradient
  - Remarks concerning $\beta < 1$ cavities
  - Simulation of $Q(E_a)$
    - Deterministic parameters
  - Stochastic parameters
  - Look towards other laboratories
    - CERN (1985)
    - DESY
    - ORNL/JLAB
- Choice of operating temperature T_b and frequency ω
  - Power grid – beam transfer efficiency (T_b, ω)
  - Remarks concerning cryostat
- Concluding remarks

Choice of accelerating gradient
Remarks concerning $\beta < 1$ cavities
TM waves in waveguides of arbitrary cross section

Electromagnetic waves guided along a uniform system in z direction

Transverse magnetic waves

Cylindrical symmetry

$$\left.\begin{array}{l} \nabla^2 \vec{E} = -k^2 \vec{E} \\ \nabla^2 = \nabla_{xy}^2 + \dfrac{\partial^2}{\partial z^2} \\ \dfrac{\partial^2}{\partial z^2} = \gamma^2 \end{array}\right\} \Rightarrow \nabla_{xy}^2 \vec{E} = -(\underbrace{\gamma^2 + \overbrace{k^2}^{\left(\frac{\omega}{c}\right)^2}}_{k_c^2}) \vec{E} \Rightarrow \nabla_{xy}^2 E_z = \frac{\partial^2 E_z}{\partial r^2} + \frac{1}{r}\frac{\partial E_z}{\partial r} + \frac{1}{r^2}\underbrace{\frac{\partial^2 E_z}{\partial \varphi^2}}_{=0} = -k_c^2 E_z$$

$$\gamma = 0 \Rightarrow \frac{\partial^2 E_z}{\partial r^2} + \frac{1}{r}\frac{\partial E_z}{\partial r} + \left(\frac{\omega}{c}\right)^2 E_z = 0$$

Pillbox resonator with metallic wall at $r = R$:
$\boldsymbol{E_z = 0}$

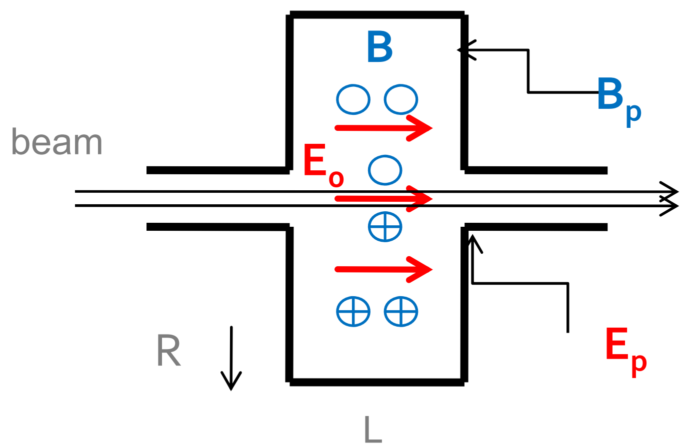
$$E_z(r) = E_0 \cdot J_0\left(\frac{\omega}{c} \cdot r\right) = E_0 \cdot J_0\left(2.405 \cdot \frac{r}{R}\right)$$

Choice of accelerating gradient

Remarks concerning $\beta < 1$ cavities

Definition of accelerating gradient

The unavoidable beam tube opening is considered to be small compared to λ



$$E(r,t) = J_0\left(\frac{2.405 \cdot r}{R}\right) \cdot E_0 \sin(\omega_0 \cdot t)$$

$$t(z) = z / (\beta \cdot c)$$

$$L = \beta \cdot \frac{\lambda}{2}$$

$$W\big|_{r=0} = e\int_0^L E(r=0, t(z))dz = eE_0 \cdot \int_0^L \sin(\omega_0 \cdot z/(\beta \cdot c))dz =$$

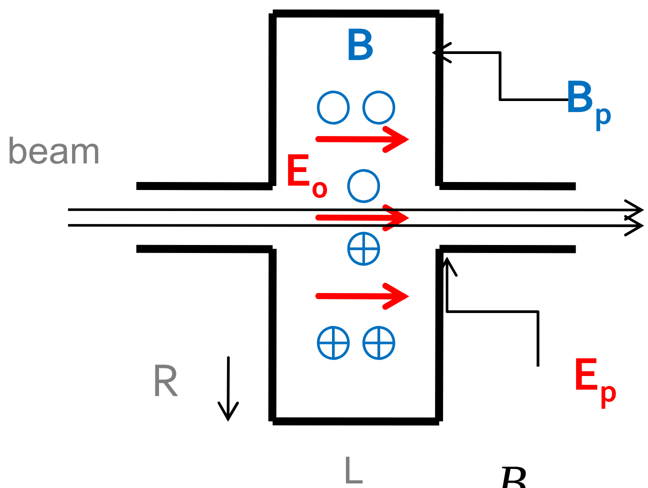
$$V_a = \frac{W}{e} = \frac{E_a \cdot L}{e} = E_0 \cdot \frac{2}{\pi} \cdot L \Rightarrow E_a = \frac{2E_0}{\pi}$$

Choice of accelerating gradient

Remarks concerning $\beta < 1$ cavities

Peak fields

The peak surface electric and magnetic fields constitute the ultimate limit for the accelerating gradient => minimize the ratio E_p/E_a and B_p/E_a.



$$E = J_0\left(\frac{2.405\cdot r}{R}\right)\cdot E_0 e^{i\omega_0 t}$$

$$B_\varphi(r) = \frac{i}{c} J_1\left(\frac{2.405\cdot r}{R}\right)\cdot E_0 e^{i\omega_0 t}$$

$$E_a = \frac{2E_0}{\pi}$$

$$\frac{B_p}{E_a} = \underset{r\in[0,R]}{Max}\frac{\frac{1}{c}J_1\left(\frac{2.405\cdot r}{R}\right)\cdot E_0}{\frac{2E_0}{\pi}} = \frac{0.581865\cdot\pi}{2\cdot c} \approx 3.07\left[\frac{\mathrm{mT}}{\mathrm{MV/m}}\right]$$

$$\frac{E_p}{E_a} = \underset{r\in[0,R]}{Max}\frac{J_0\left(\frac{2.405\cdot r}{R}\right)\cdot E_0}{\frac{2E_0}{\pi}} = \frac{\pi}{2} \approx 1.57$$

Choice of accelerating gradient

Remarks concerning $\beta < 1$ cavities

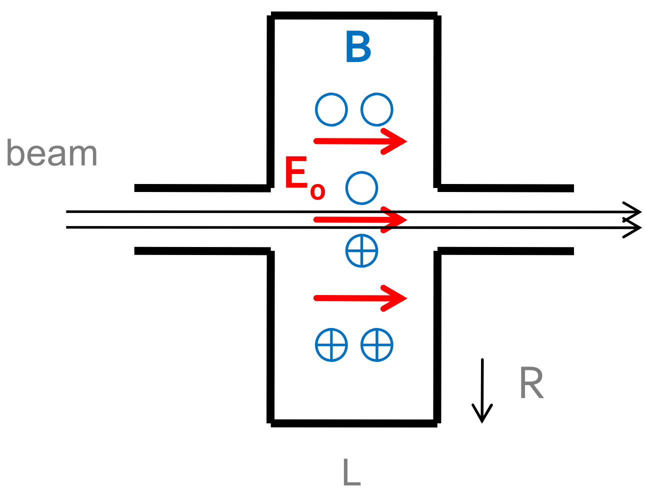
Radial field distribution of $\beta < 1$ resonator

For an accelerating cavity (π – mode, $\beta = 1$):

$$\gamma \cdot L = i\pi = i\gamma \cdot c \cdot \frac{T}{2} = i\gamma \cdot \frac{c}{2 \cdot f} = i\gamma \cdot \frac{c \cdot \pi}{2 \cdot \pi \cdot f} = i\gamma \cdot \frac{c \cdot \pi}{\omega} \Rightarrow \gamma = i\frac{\omega}{c}$$

and for $\beta < 1$):

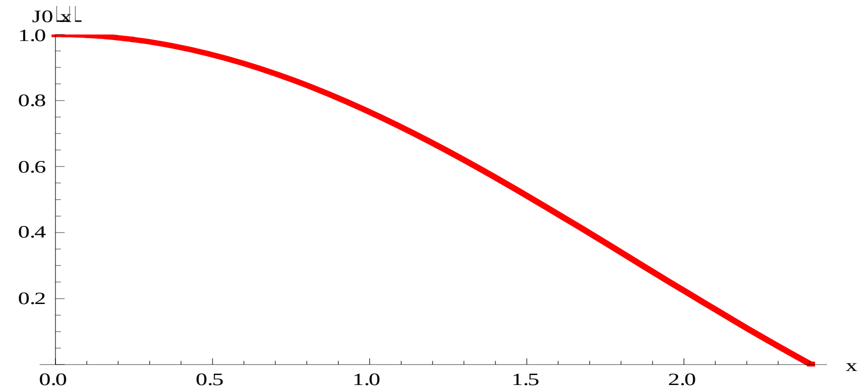
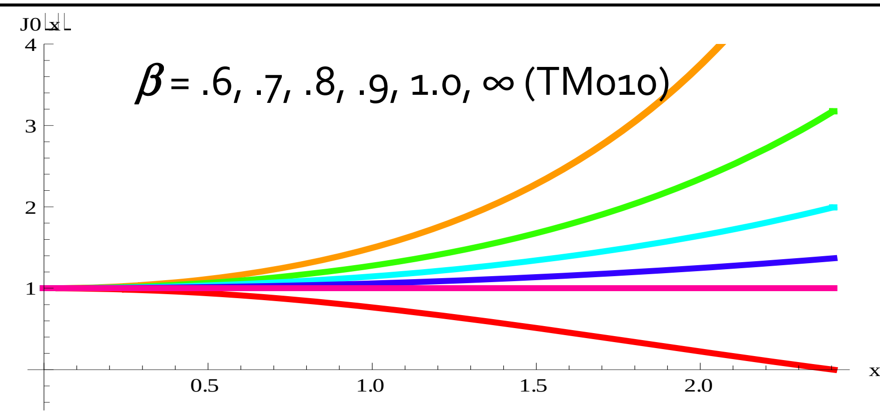
$$\gamma \cdot \boldsymbol{\beta} \cdot L = i\pi = \ldots = i\gamma \cdot \boldsymbol{\beta} \cdot \frac{c \cdot \pi}{\omega} \Rightarrow \gamma = i\frac{\omega}{\boldsymbol{\beta} \cdot c}$$



$$\nabla_{xy}^2 E_z = -(\gamma^2 + \overbrace{k^2}^{(\omega/c)^2})E_z$$

$$\nabla_{xy}^2 E_z + \gamma^2(1 + \frac{k^2}{\gamma^2})E_z = \nabla_{xy}^2 E_z - \left(\frac{\omega}{c}\right)^2 (\frac{1}{\boldsymbol{\beta}^2} - 1)E_z = 0$$

Choice of accelerating gradient
Remarks concerning β< 1 cavities
Comparison pillbox resonator – acc. cavity

	Differential equation in the vicinity of the rotational symmetry axis Solution for fundamental transverse magnetic mode	Graph of solution
TM010	Bessel function J_0 $\frac{\partial^2 E_z}{\partial r^2} + \frac{1}{r}\frac{\partial E_z}{\partial r} + \left(\frac{\omega}{c}\right)^2 E_z = 0$ $E_z(r) = E_0 \cdot J_0\left(\underbrace{2.405 \cdot r/R}_{x}\right)$ $J_0(x) = 1 - \frac{x^2}{4} + \frac{x^4}{64} - \frac{x^6}{2304} + \ldots$	
Acc. Cavity	Modified Bessel function I_0 $\frac{\partial^2 E_z}{\partial r^2} + \frac{1}{r}\frac{\partial E_z}{\partial r} + \left(\frac{\omega}{c}\right)^2 (1 - \frac{1}{\beta^2}) E_z = 0$ $E_z(r) = E_0 \cdot I_0\left(\underbrace{2.405 \cdot \sqrt{\beta^{-2} - 1} \cdot r/R}_{x}\right)$ $I_0(x) = 1 + \frac{x^2}{4} + \frac{x^4}{64} + \frac{x^6}{2304} + \ldots$	

Choice of accelerating gradient

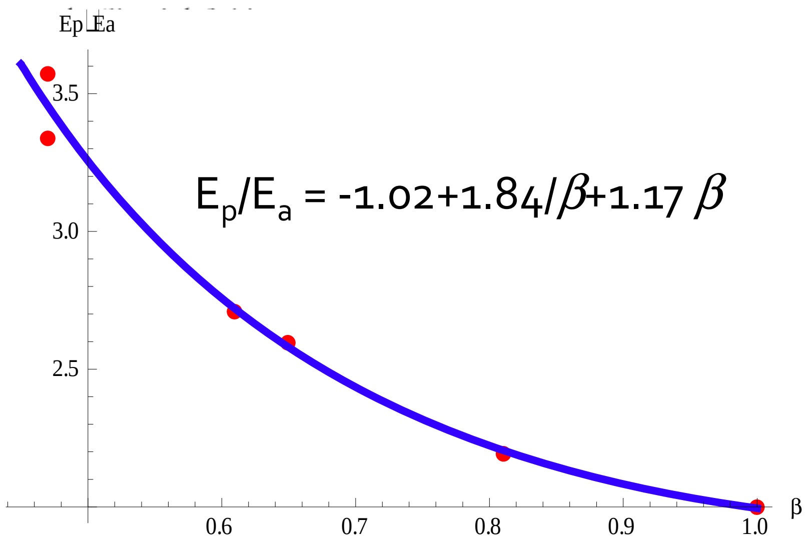
Remarks concerning $\beta < 1$ cavities

Technically realized peak fields for $\beta < 1$ resonator

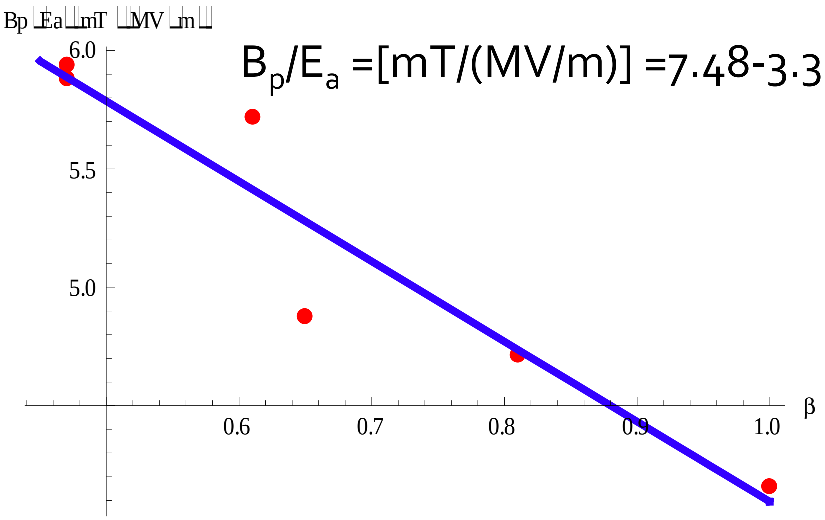
Table 4.9: Medium-β multi-cell cavity parameters (bulk-niobium structures only)

Project	f [MHz]	β	E_{peak}/E_{acc}	H_{peak}/E_{acc} [mT/(MV/m)]	N_{cell}	$(R/Q)/N_{cell}$ [Ω]
RIA	805	0.47	3.34	5.94	6	26.67
TRASCO	704	0.47	3.57	5.88	5	31.60
SNS medium-β	805	0.61	2.71	5.72	6	46.50
CEA/CNRS	704	0.65	2.60	4.88	5	63.00
SNS high-β	805	0.81	2.19	4.72	6	80.50
TTF	1300	1.00	2.00	4.16	9	115.11

(R/Q)



$E_p/E_a = -1.02+1.84/\beta+1.17\,\beta$



$B_p/E_a = [mT/(MV/m)] = 7.48-3.38\beta$

Choice of accelerating gradient

Simulation of $Q(E_a)$

Deterministic parameters – The BCS surface resistance R_s

CW operation, using Mathematica with

- fix parameters:
  - wall thickness = 3 mm
  - Nb (*RRR* = 100)
  - geometrical length $\beta = 1$
  - residual resistance R_{res}
- with T-dependent
  - surface resistance $R_s\,(T_c/T)$
  - thermal conductivity λ
  - nucleate boiling heat transfer coefficient α
  - Kapitza resistance in HeII
- under the constraints of
  - max. magnetic field of
    B_p = 200 mT·[1-$(T/T_c)^2$]
  - max. nucleate boiling heat flux in He of 0.5 W/cm²
  - max. heat flux in HeII of 0.5 W/cm²

$$R_s^{BCS} / \text{n}\Omega = 10^5 \cdot (f / \text{GHz})^2 \cdot \frac{\exp\left(-\frac{18}{T/\text{K}}\right)}{T/\text{K}}$$

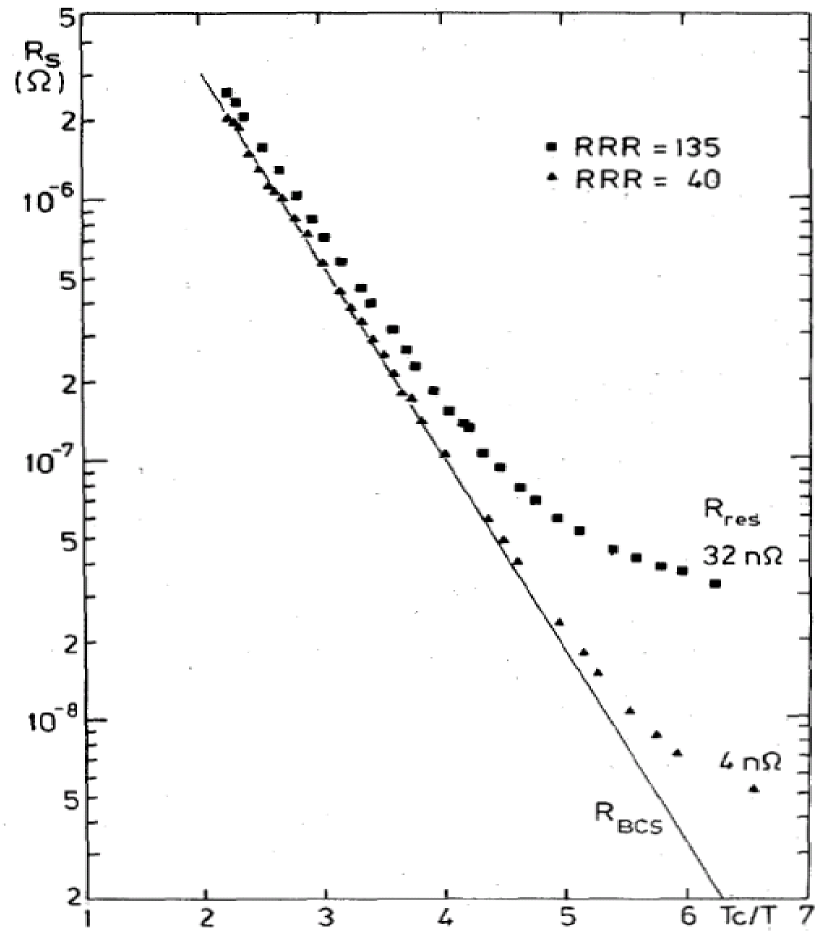


Fig. 2: Surface resistance $R_s(T)$ of two 3 GHz cavities, fabricated from niobium of different purity. $R_s(T)$ is the sum of the temperature dependent part R_{BCS} and the residual resistance R_{res}.

Choice of accelerating gradient

Deterministic parameters

Nucleate boiling heat transfer – Kapitza resistance

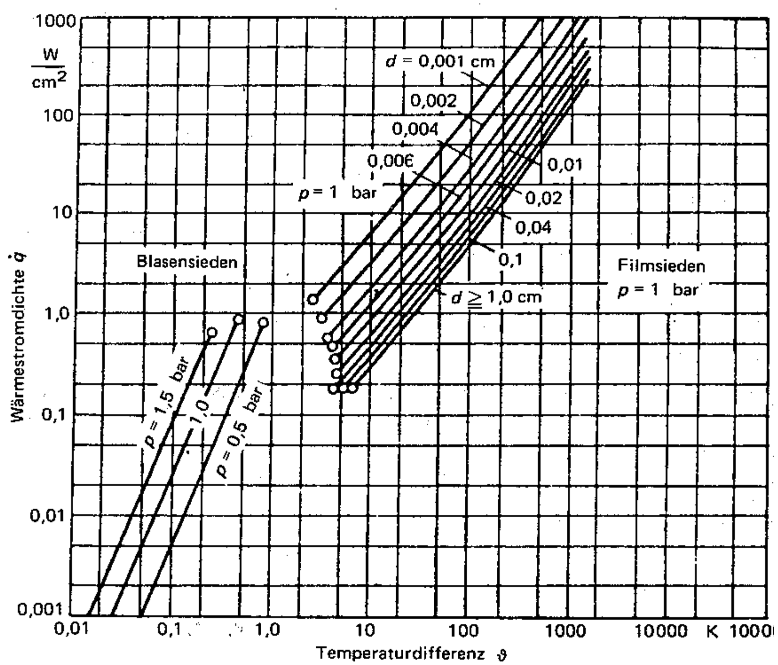
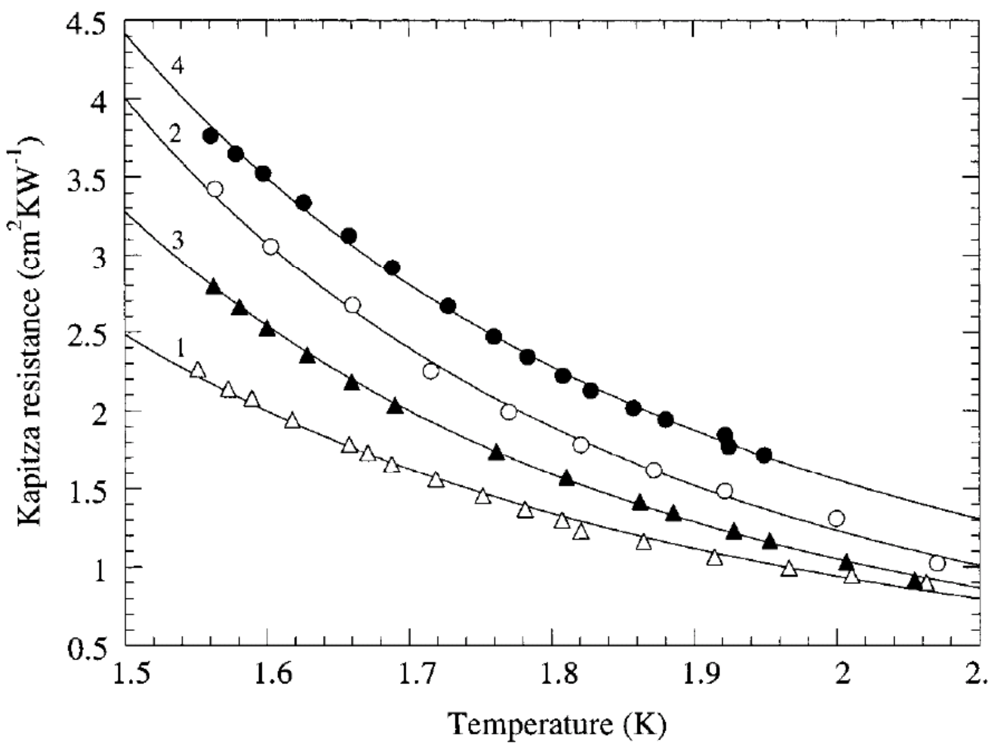


Bild 5-14. Blasen- und Filmverdampfung bei Helium.
d Durchmesser des Heizers



H. Frey, R. A. Haefer, Tieftemperaturtechnologie, VDI-Verlag, Düsseldorf 1981

J. Amrit and M. X. Francois, Journal of Low Temperature Physics 119 (2000) 27

Choice of accelerating gradient

Deterministic parameters

Thermal conductivity

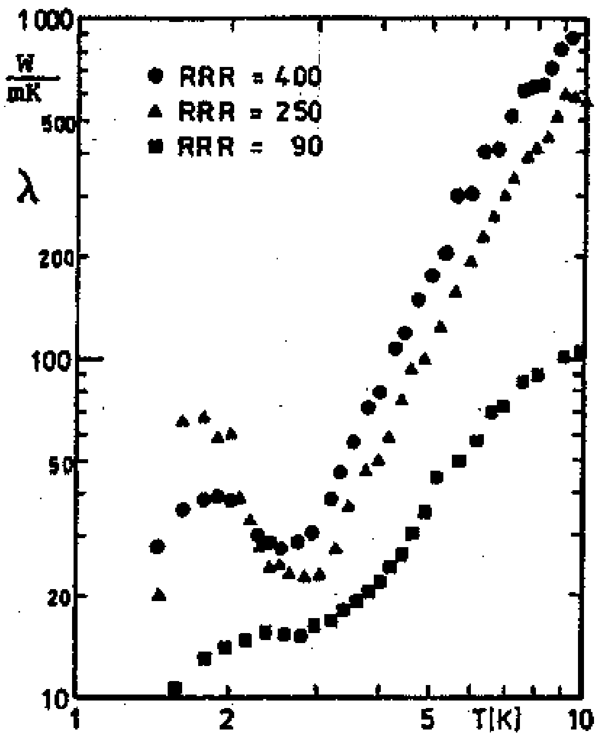


Figure 4: Thermal conductivity of Nb [4] for various purity levels. (RRR = residual resistivity ratio)

A. W. Chao, M. Tigner, Handbook of Accelerator Physics, World Scientific, Singapore 1999

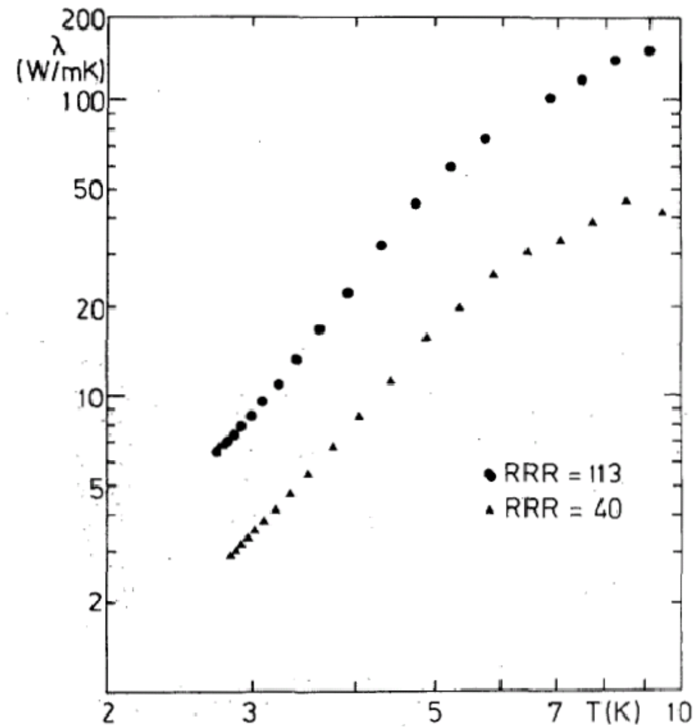
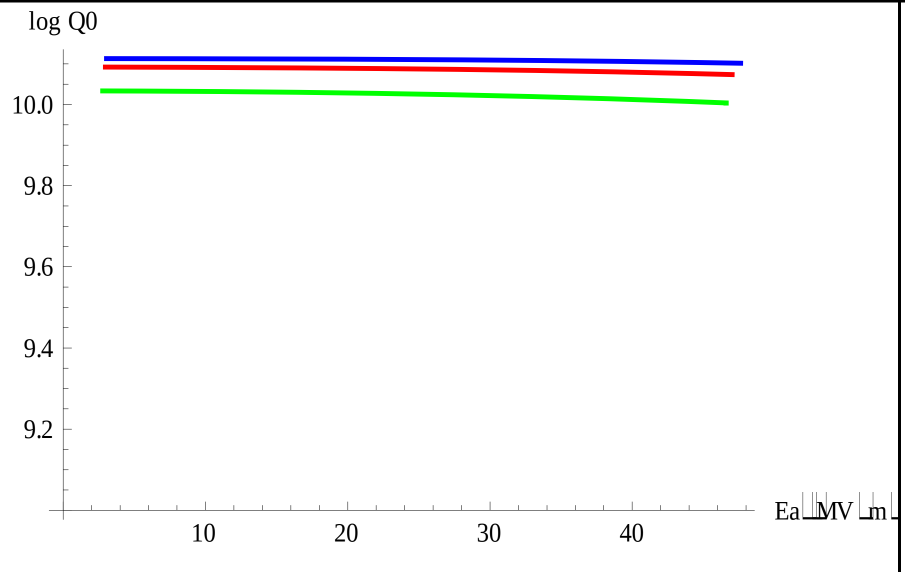
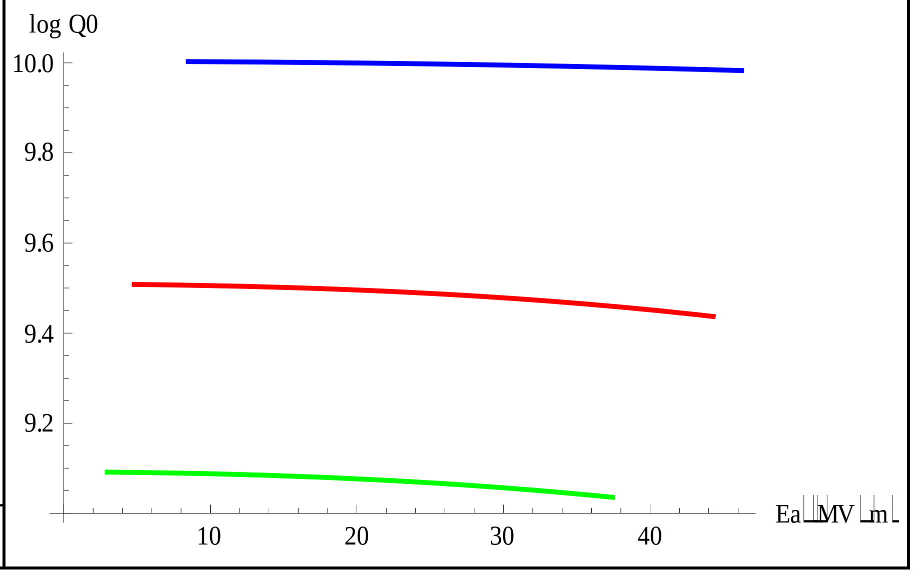


Fig. 1: Thermal conductivity of reactor grade niobium (RRR=40) and niobium of higher purity (RRR=113)

H. Lengeler, W. Weingarten, G. Müller, H. Piel, IEEE TRANSACTIONS ON MAGNETICS **MAG-21** (1985) 1014

Choice of accelerating gradient
Deterministic parameters

Results of simulation : $Q(E_a)/10^9$, 704 MHz

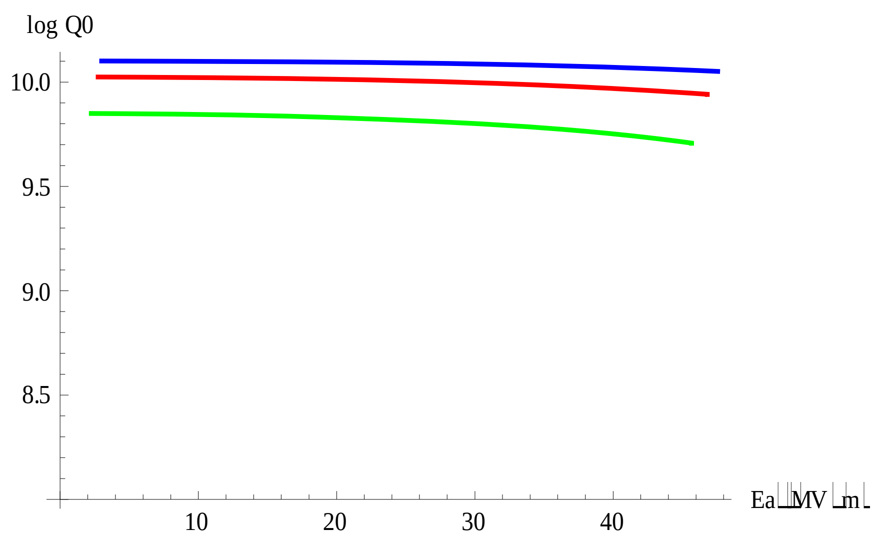
Superfluid helium T = 1.5, 1.8, 2.1 K Kapitza resistance heat transfer RRR = 90 3 mm wall thickness	Normal helium T = 2.2, 3.3, 4.5 K Nucleate boiling heat transfer RRR = 90 3 mm wall thickness
	

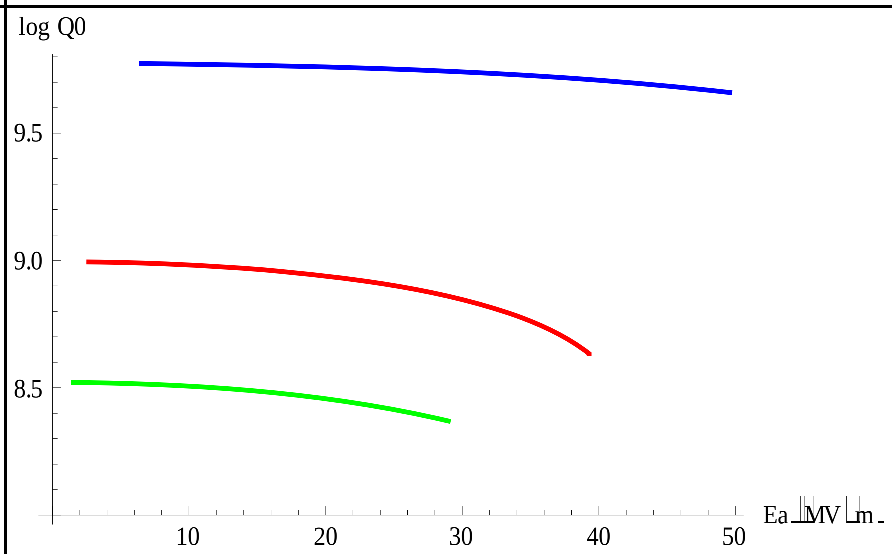
Choice of accelerating gradient

Deterministic parameters

Results of simulation : $Q(E_a)$)/10^9, 1408 MHz

Superfluid helium T = 1.5, 1.8, 2.1 K Kapitza resistance heat transfer RRR = 90 3 mm wall thickness	Normal helium T = 2.2, 3.3, 4.5 K Nucleate boiling heat transfer RRR = 90 3 mm wall thickness





Choice of accelerating gradient

Other deterministic parameters (2nd order importance)

Influencing quantity	Impact quantity	Physical explanation	Cure
External static magnetic field B_{ext}	Residual surface resistance	Creation of vortices	Shielding of ambient magnetic field by Mu-metal / Cryoperm
Residual resistivity ratio *RRR*	BCS surface resistance	Mean free path dependence of R_{res}	Annealing steps during ingot production/after cavity manufacture
Ratio peak magnetic field to accelerating gradient B_p/E_a	Max. accelerating gradient	Critical magnetic field as ultimate gradient limitation	Optimization of cavity shape
Nb-H precipitate	Q-value / acc. gradient (Q-disease)	Lowering of T_c/B_c at precipitates of Nb-H	T-control during chemical polishing Degassing @ 700 °C Fast cool-down

Stochastic parameters - CERN results (1985)

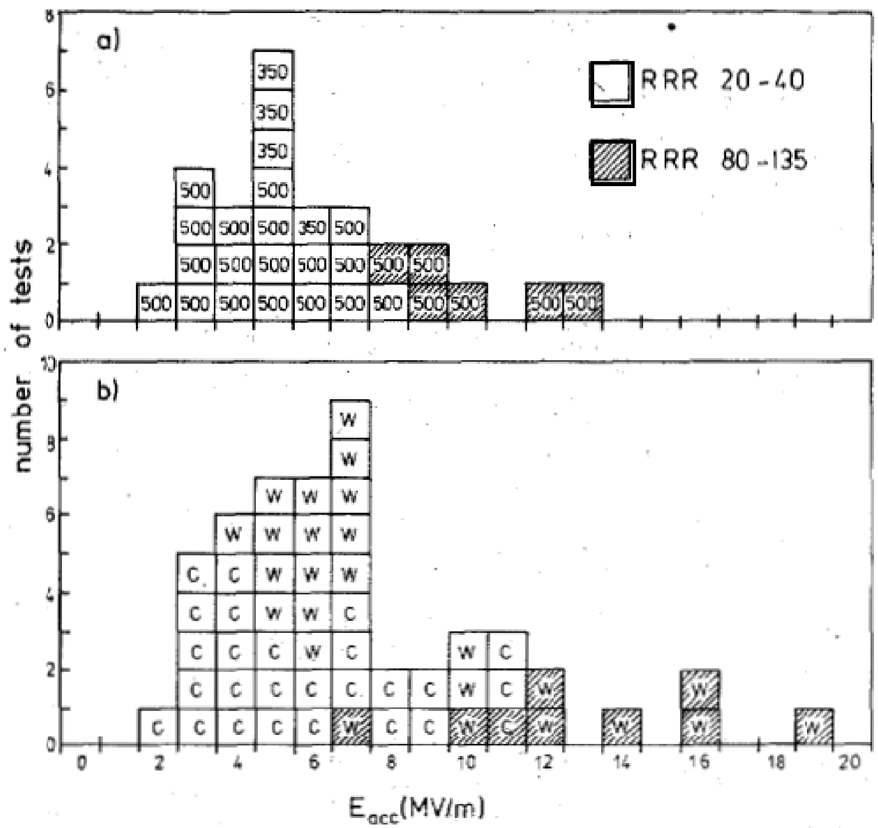
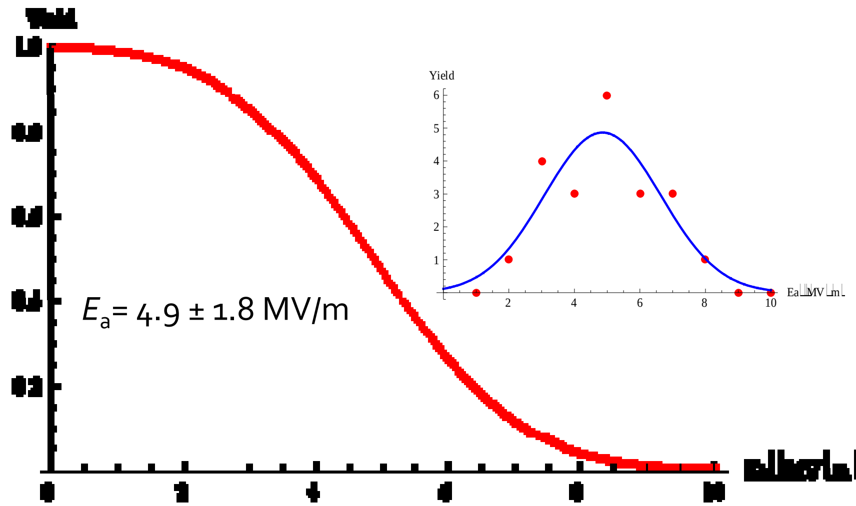
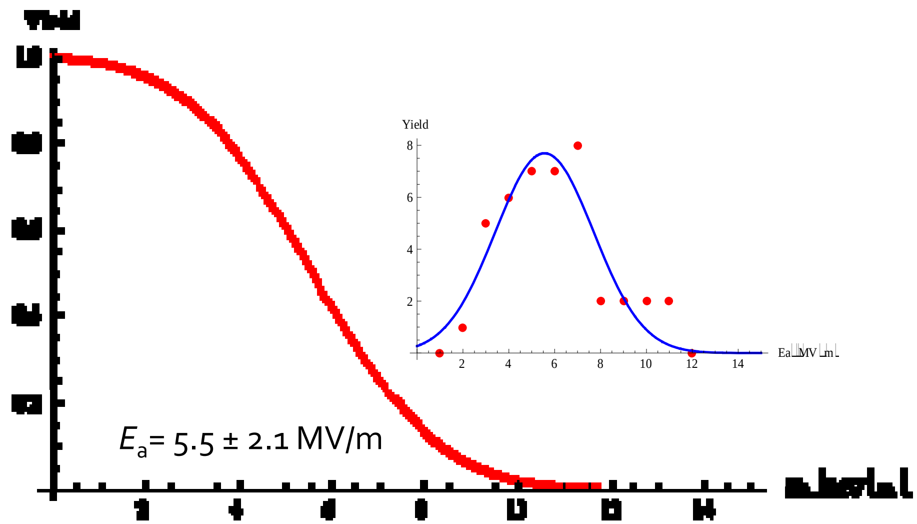


Fig. 3: Histogram of test results for single cell cavities from niobium of different RRR
a) 500 and 350 MHz
b) 3 GHz (CERN and Wuppertal)

H. Lengeler, W. Weingarten, G. Müller, H. Piel, IEEE TRANSACTIONS ON MAGNETICS **MAG-21** (1985) 1014





Choice of accelerating gradient
Stochastic parameters

DESY results

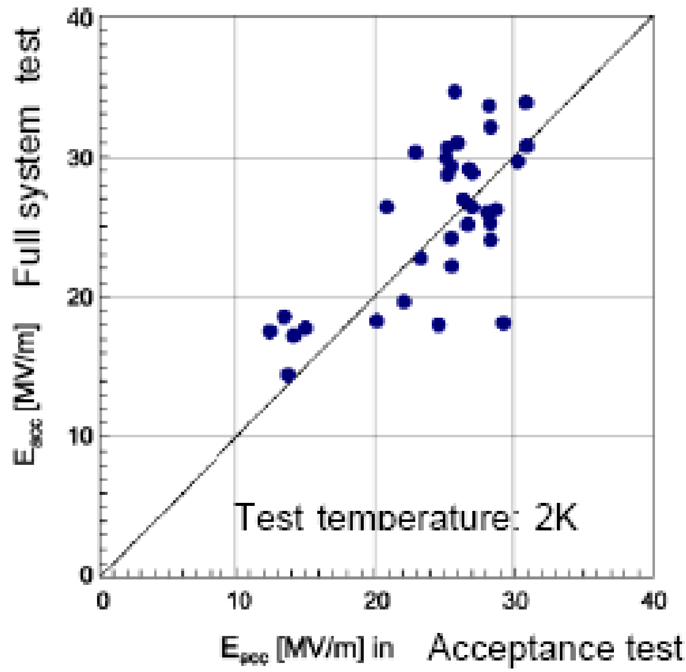


Figure 5: Comparison of cw acceptance test with full systems test (without beam)

No significant degradation of cavity performance between acceptance tests and full system tests.

Choice of accelerating gradient
Stochastic parameters - DESY results
Q (Ea)

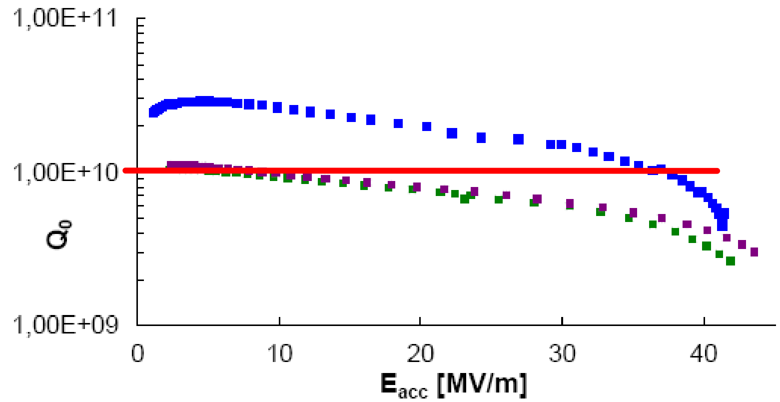


Figure 7: Example excitation curves of three welded electropolished niobium single-cell cavities. Test was done at 1.6 and 2K [9].

A residual surface resistance corresponding to a Q-value of 10^{10} at the operating gradient presents a challenge.

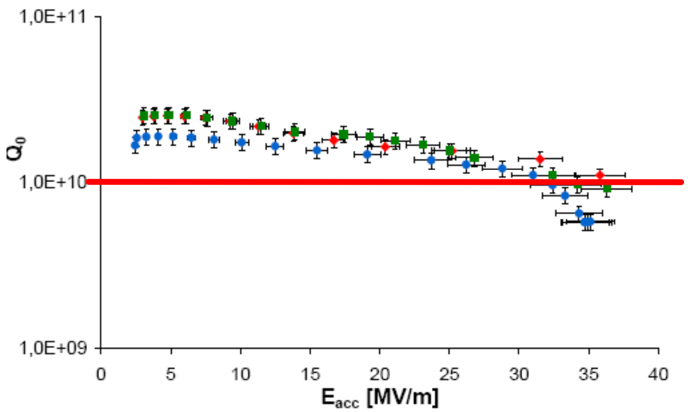


Figure 9: CW test results on three electropolished 9-cell resonators of the TESLA type from the last production series. Test was done at 2K.

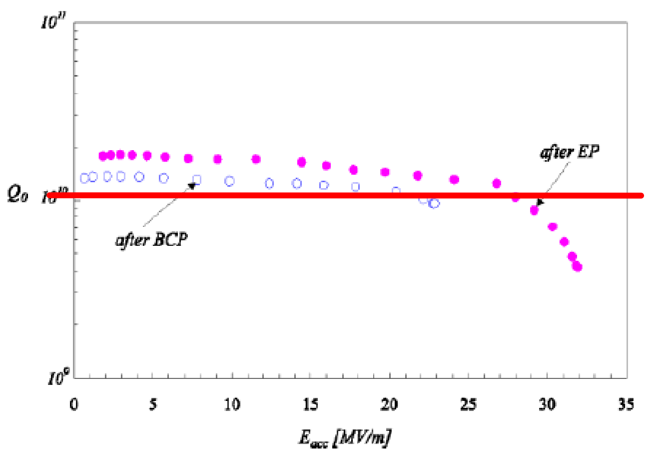


Figure 8: Result on an electropolished 9-cell cavity from the first production series. A clear improvement is seen as compared to its behavior after etching (BCP). Test was done at 2K [1].

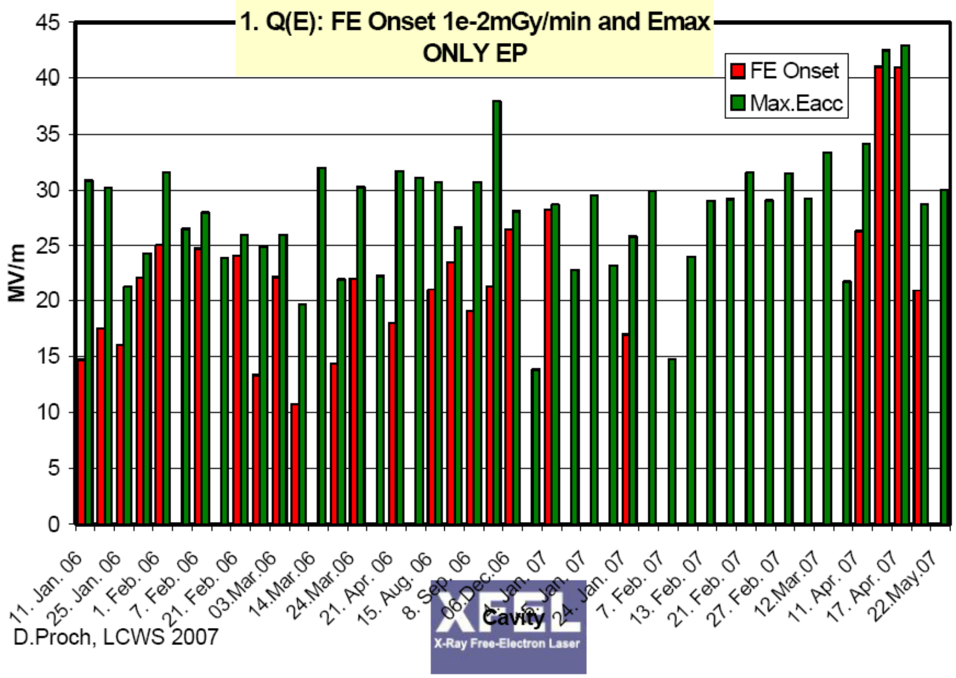
Choice of accelerating gradient
Stochastic parameters - DESY results

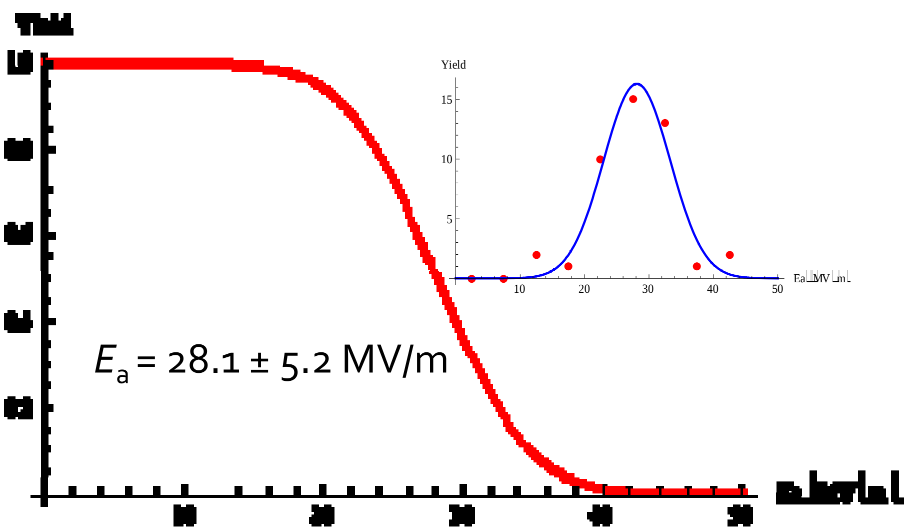
Series tests E_a

Development of Field Emission since Jan 06

compiled by D.Reschke

- Analysis of 1. Q(E)-results **only EP cavities** (all tests, not preparations):



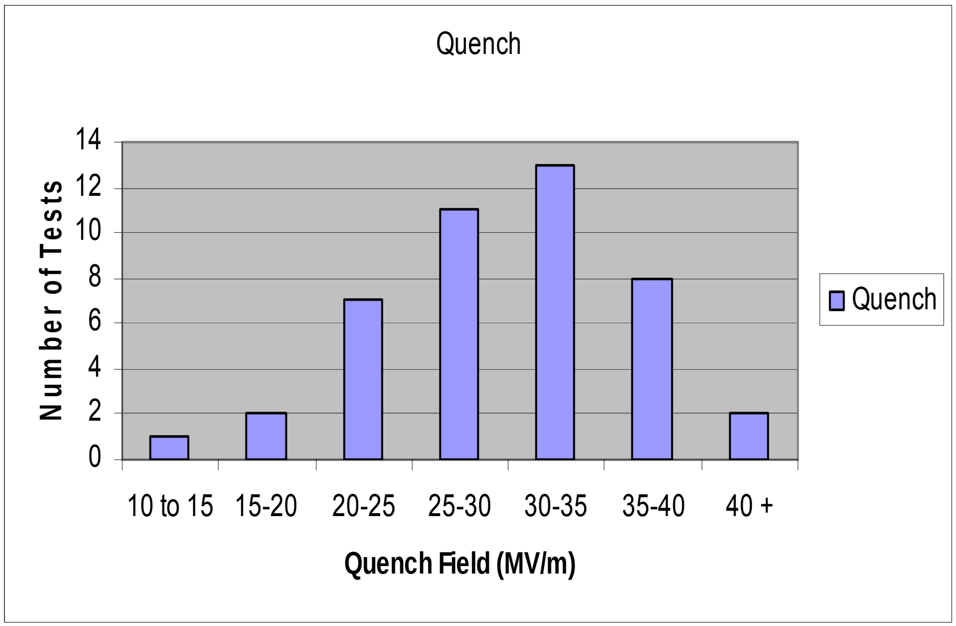


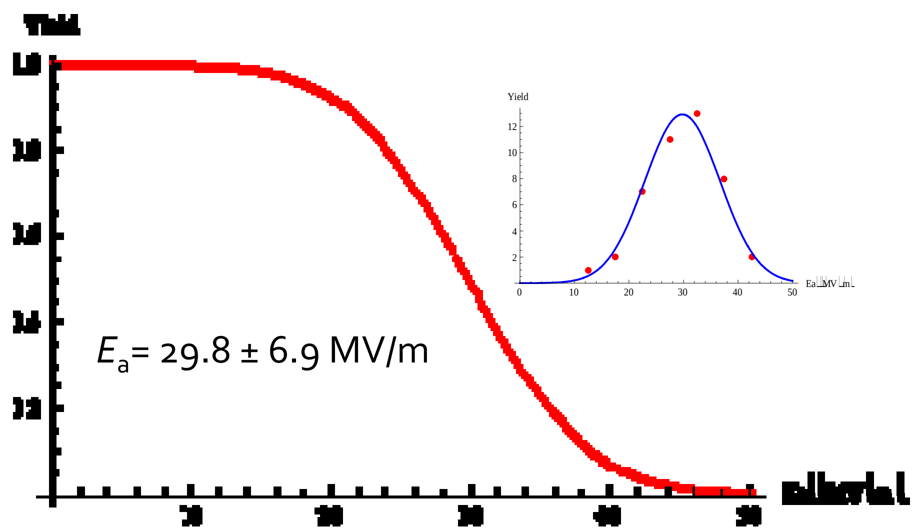
$E_a = 28.1 \pm 5.2$ MV/m

Choice of accelerating gradient
Stochastic parameters - DESY results

Gradient spread Due to Quench

Probability of “Quench Only” DESY 9-cell Cavities (EP cavities only)

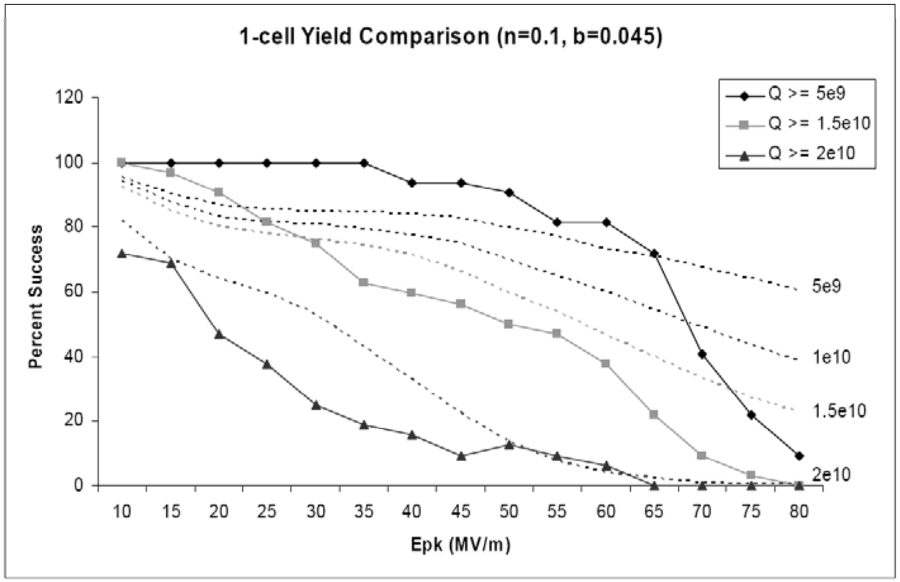




Compiled by H.Padamsee from DESY Data Base, TTC Meeting at DESY, January 14 - 17, 2008 https://indico.desy.de/conferenceOtherViews.py?view=standard&confId=401

Choice of accelerating gradient
Stochastic parameters - DESY results

1 cell vs. 9 cells 1.3 GHz



Figures 5: Simulated vs. observed yield profiles for 1-cells

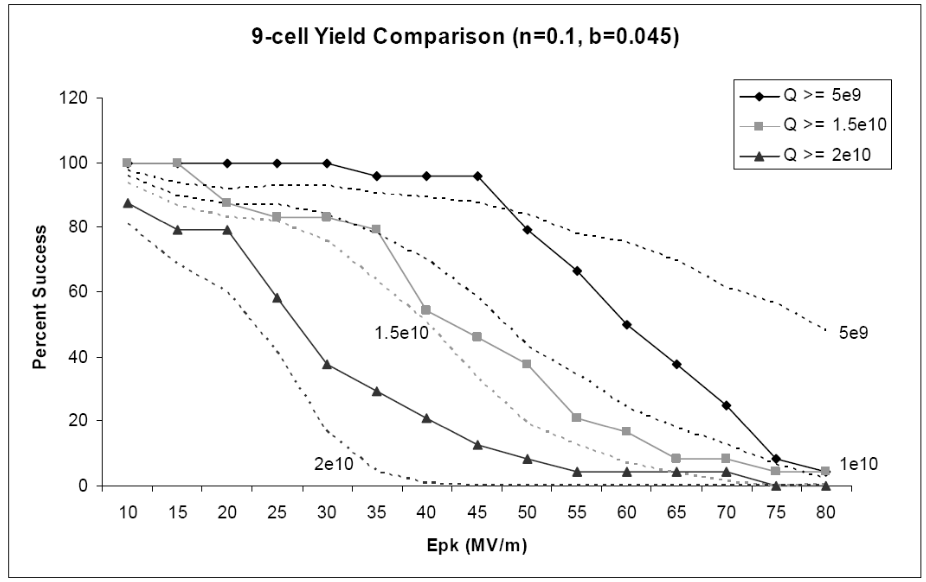


Figure 6: Simulated vs. observed yield profiles for 9-cells

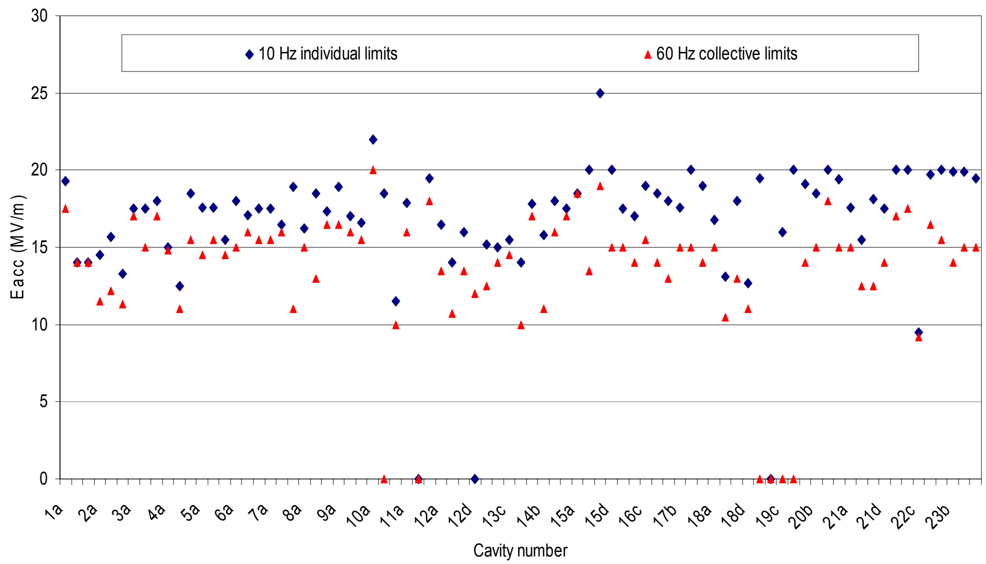
From TESLA report 2008-02
J. Wiener, H. Padamsee

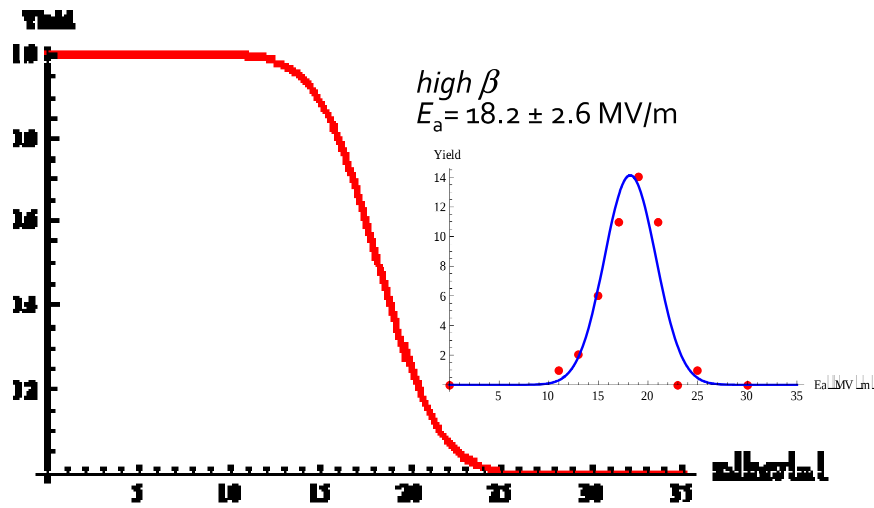
On all cavities prepared by EP + low-temp baking:
1-cell or 9-cells seem not to show different results

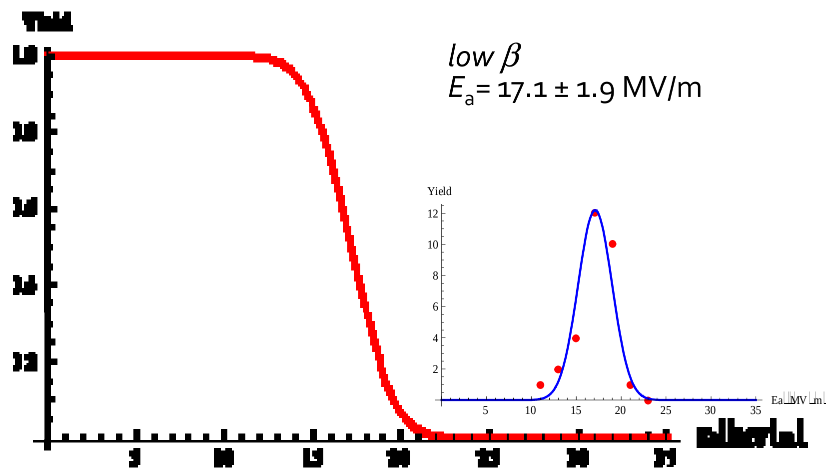
Choice of accelerating gradient

Stochastic parameters

ORNL/JLAB results







Source: I. E. Campisi and S.–H. Kim, **SNS Superconducting Linac operating experience and issues**,
Accelerator Physics and Technology Workshop for Project X, November 12-13, 2007
http://projectx.fnal.gov/Workshop/Breakouts/HighEnergyLinac/agenda.html

Choice of accelerating gradient

Stochastic parameters

Summary of results in other labs

Laboratory	$\langle E_a \rangle$ [MV/m]	ΔE_a [MV/m]	$\Delta E_a / \langle E_a \rangle$ [%]	$\langle E_a \rangle$ [MV/m] @ 90 (50) [%] processing yield *)
CERN @ 1985 350 – 500 MHz 1-cell	4.9	1.8	37	3 (4.9)
CERN/Wuppertal @ 1985 3 GHz 1-cell	5.5	2.1	38	3 (5.5)
DESY 1.3 GHz (all) ditto (quench) 9-cell	28 30	5.2 6.9	19 23	22 (28) **23 (30)**
ORNL/JLAB SNS 805 MHz β = 0.61 6-cell β = 1 (extrapolated)	17.1 23.0	1.9 2.6	11 11	15 (17) **20 (23)**
β = 0.81 6-cell β = 1 (extrapolated)	18.2 20	2.6 2.8	14 14	15 (18) **16 (20)**

*) 11 (100) [%] re-processing needed (= 1/yield)

Choice of accelerating gradient

Stochastic parameters

Influencing quantity	Impact quantity	Physical explanation	Cure
Field emission sites (foreign particles sticking to the surface, size, density)	Q – value / acc. gradient γ radiation HOM coupler quench	Modified Fowler-Nordheim-theory	Electro-polishing Assembling in dust-free air Rinsing with ultrapure water (control of resistivity and particulate content of outlet water) and alcohol High pressure ultrapure water rinsing (ditto) “He- processing” Heat treatment @ 800 – 1400 °C
Secondary emission coefficient δ	Electron-multipacting	Theory of secondary electron emission	Rounded shape of cavity Rinsing with ultrapure water Bake-out RF - Processing
Unknown	Q – slope / Q-drop (Q – value / acc. gradient)	***Unknown***	Annealing 150 °C Electro-polishing
Metallic normal-conducting inclusions in Nb	Acc. gradient	Local heating up till critical temperature of Nb	Inspection of Nb sheets (eddy current or SQUID scanning) Removal of defects (≈ 1 µm) Sufficiently large thermal conductivity (30 - 40 [W/(mK)])
Residual surface resistance	Q – value / acc. gradient	***Unknown to large extent***	Quality assurance control of a multitude of parameters

Choice of operating temperature and frequency Power grid – beam transfer efficiency (T_b, ω)

Simulation parameters

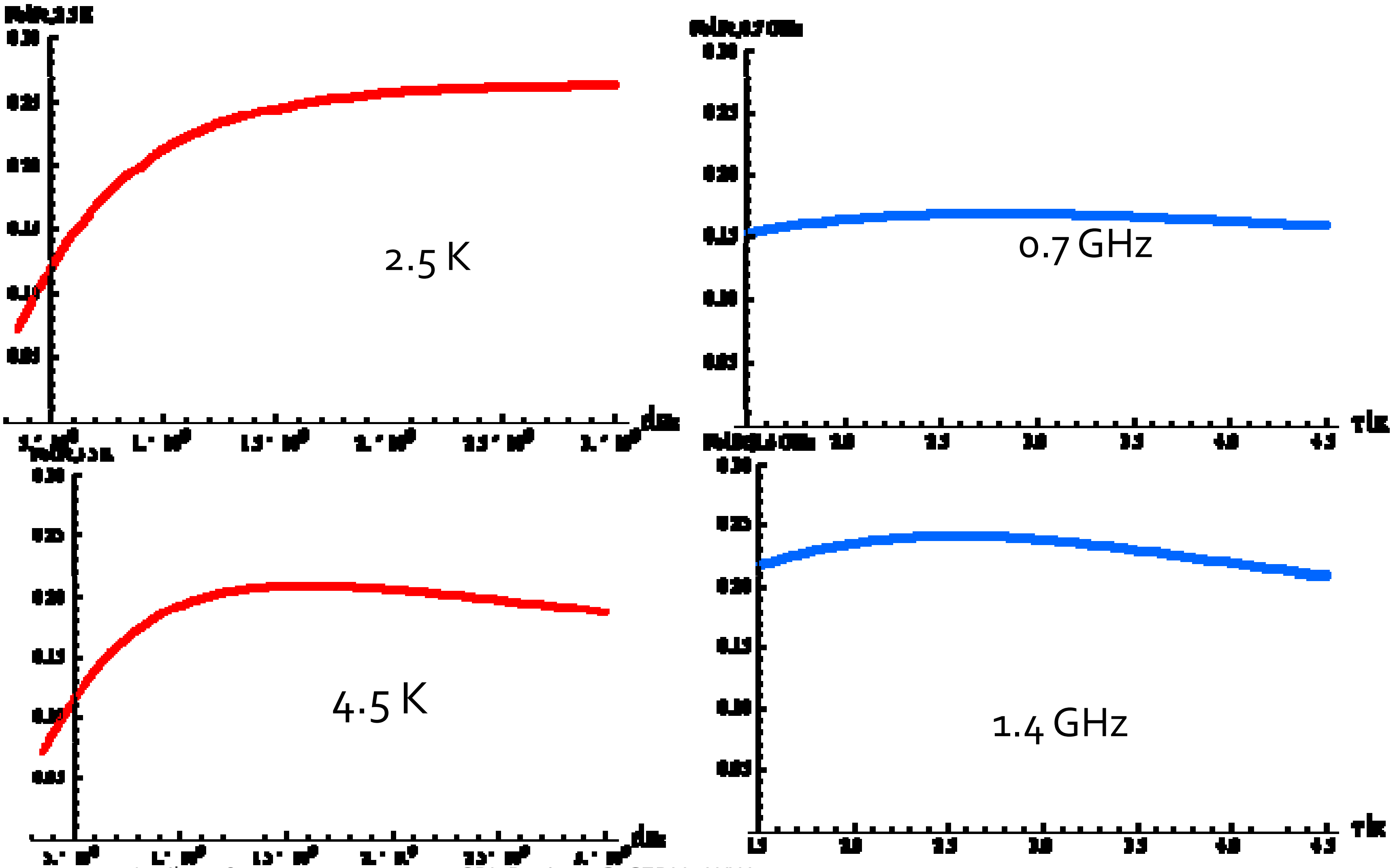
High Power SPL

$\beta = 1$
E_a = 25 MV/m
R_{res} = 24 nΩ
n = 5
τ = 0.72 msec
I_b = 40 mA
T_{in} = 0.64 GeV
T_{out} = 5 GeV
ϕ = 20 degrees
r = 50 sec^{-1}
$\eta_{real\text{-}estate}$ = 0.5
η_{Rf} = 0.4
η_{td} = 0.2
P_{cst} = 15 W/m

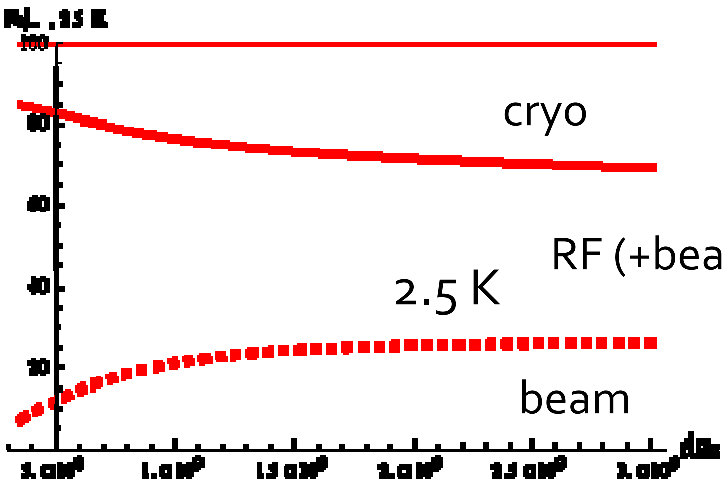
Low Power SPL

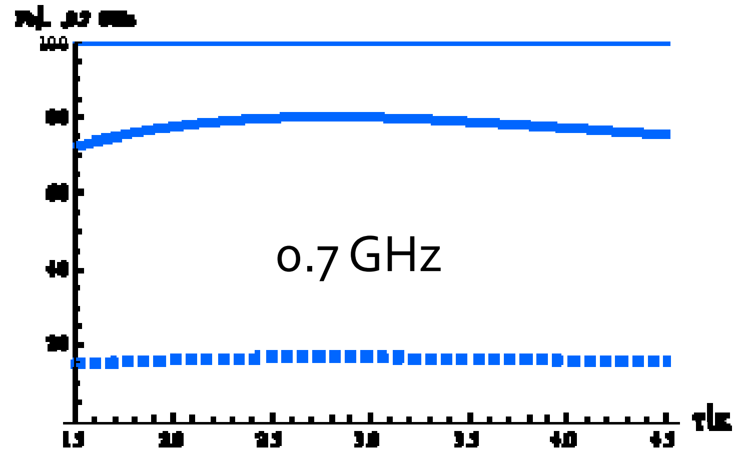
$\beta = 1$
E_a = 25 MV/m
R_{res} = 24 nΩ
n = 5
τ = 1.2 msec
I_b = 20 mA
T_{in} = 0.64 GeV
T_{out} = 4 GeV
ϕ = 20 degrees
r = 2 sec^{-1}
$\eta_{real\text{-}estate}$ = 0.5
η_{Rf} = 0.4
η_{td} = 0.2
P_{cst} = 15 W/m

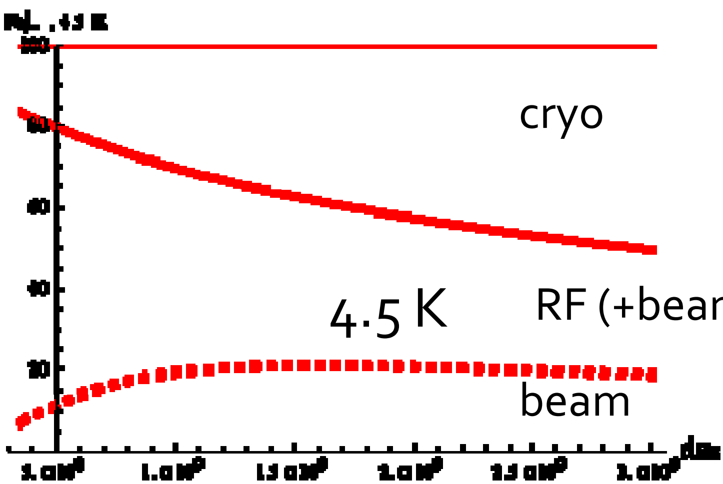
Choice of operating temperature and frequency
Power grid – beam transfer efficiency (T_b, ω)
Results high power SPL

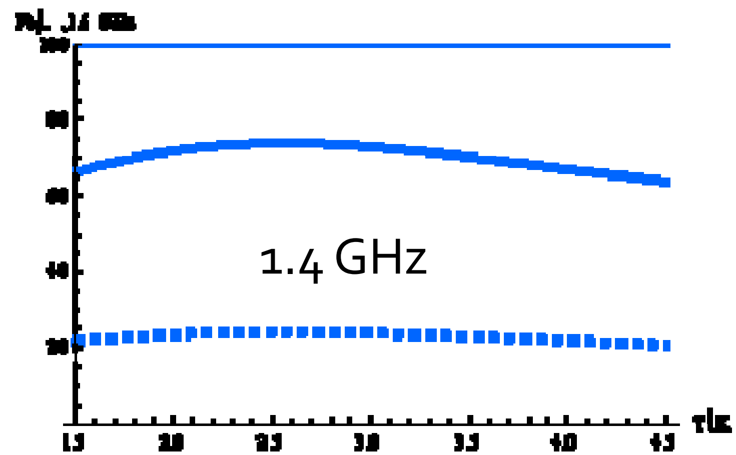


Choice of operating temperature and frequency
Results high power SPL
Total power sharing [%]



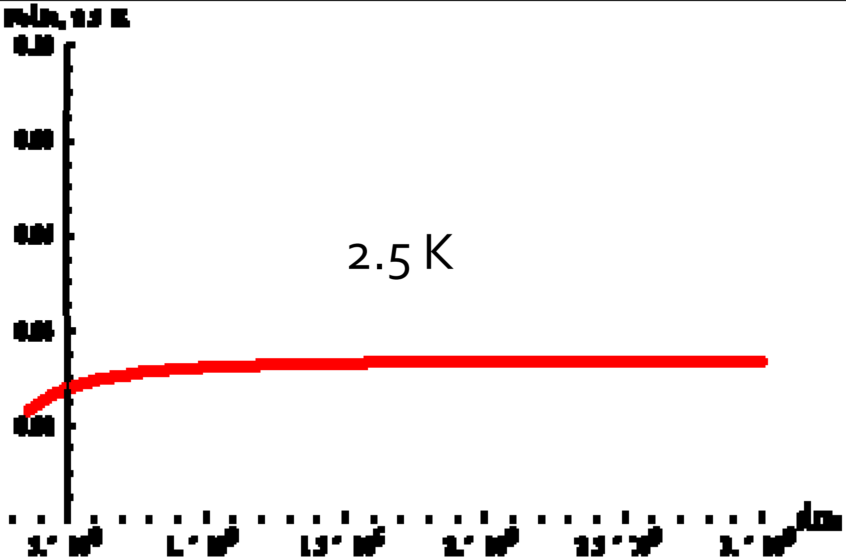


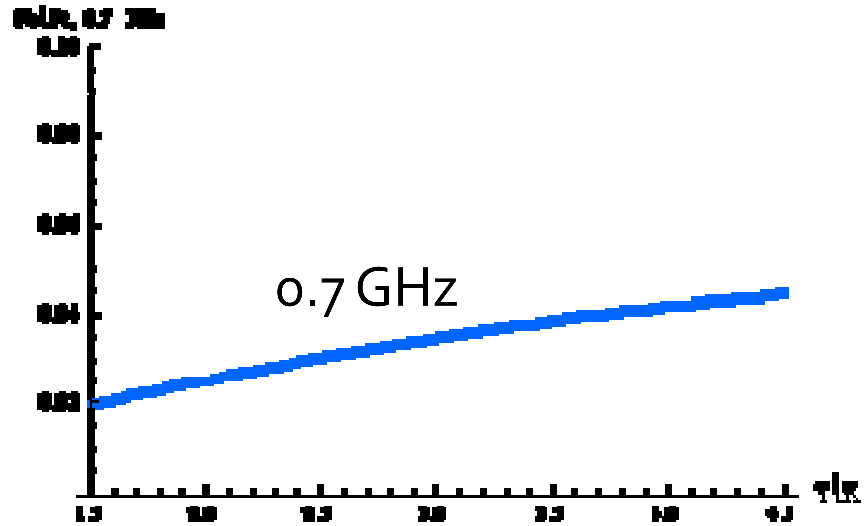


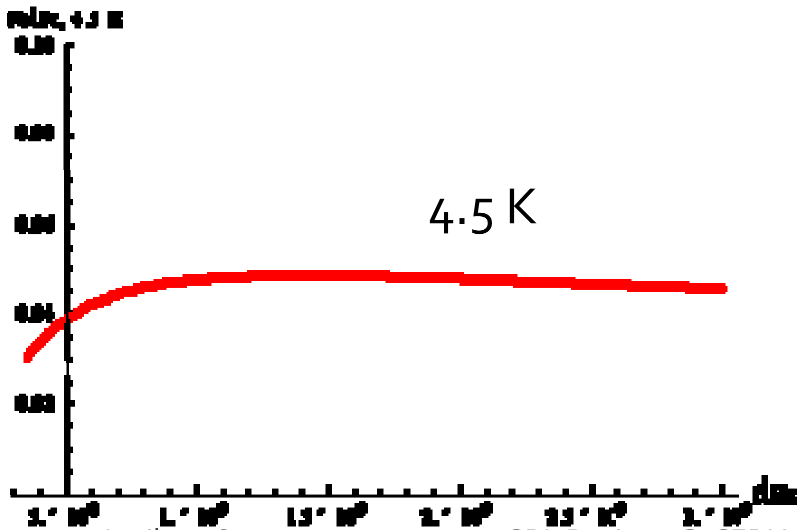


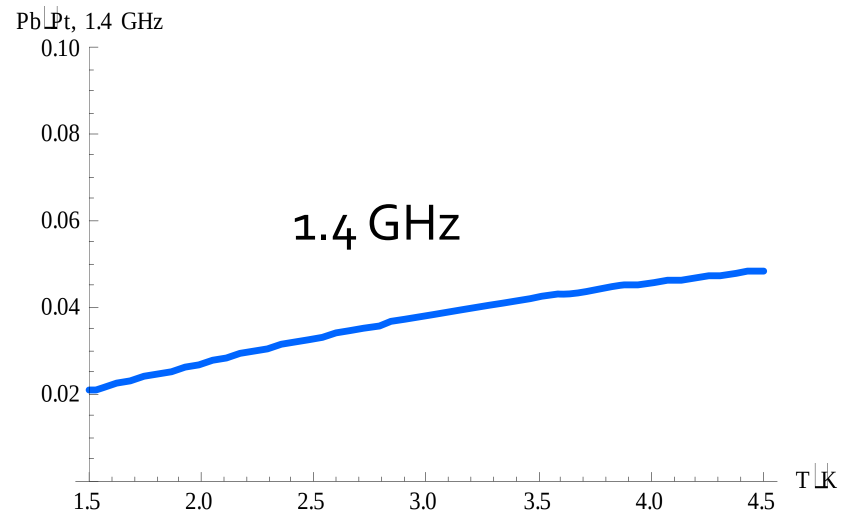
Choice of operating temperature and frequency

Power grid – beam transfer efficiency (T_b, ω)
Results low power SPL



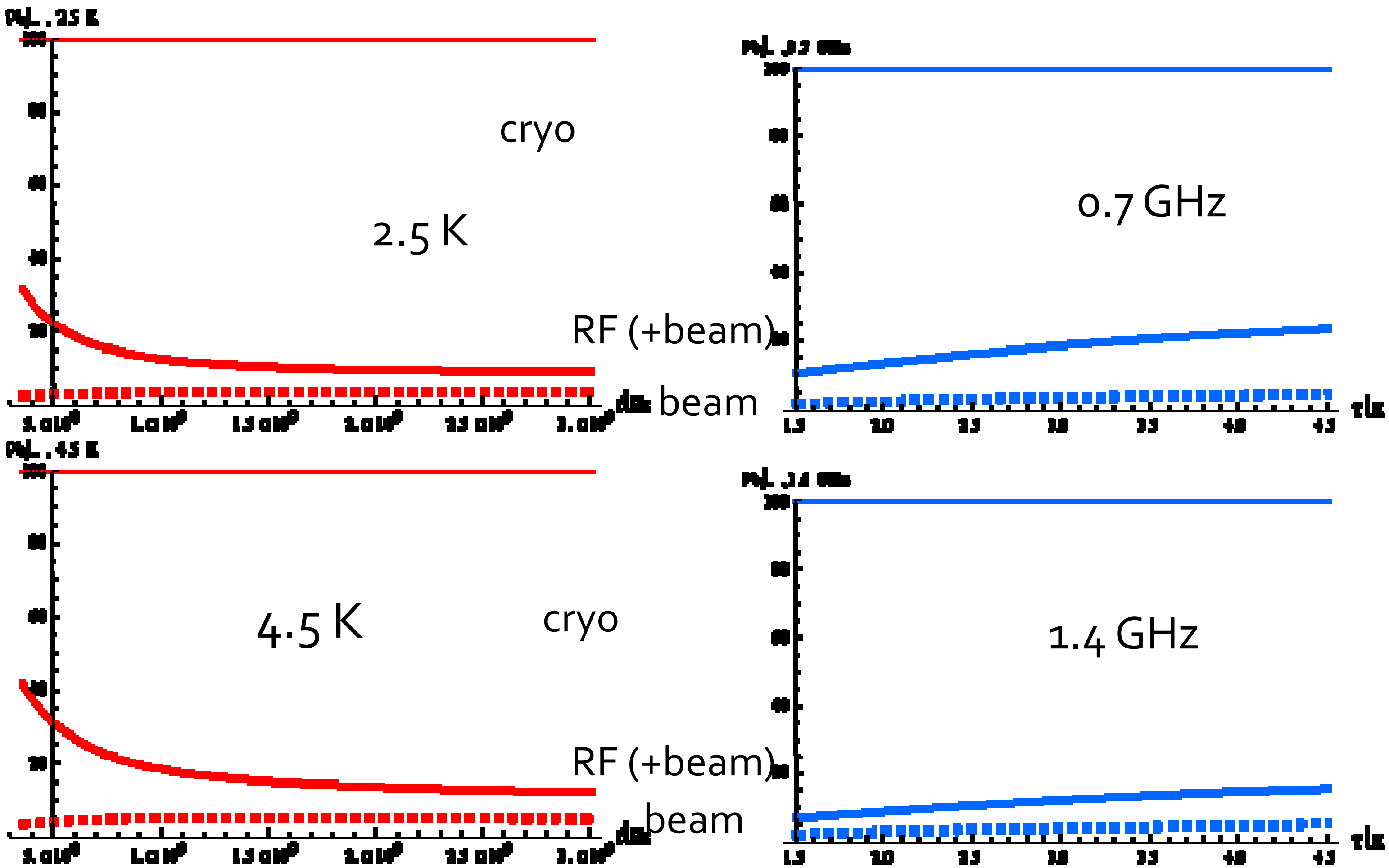






Choice of operating temperature and frequency
Results low power SPL

Total power sharing [%]



Choice of operating temperature and frequency

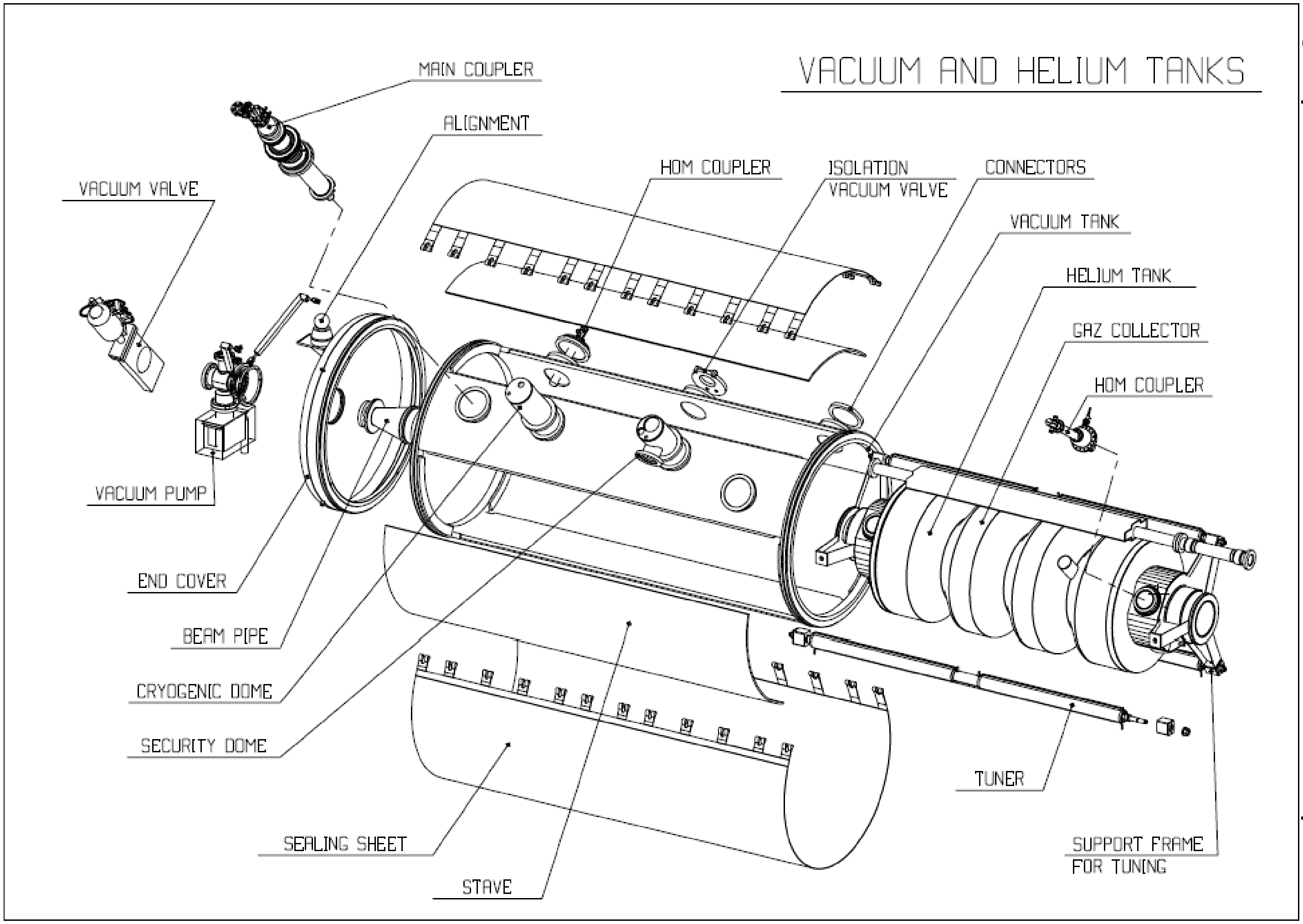
Remarks concerning cryostat

Comparison of planned and existing sc linacs

	(LEP)	LP-SPL high β	HP-SPL high β	SNS high β	Project X	XFEL	ILC
f [MHz]	352	704	704	805	1300	1300	1300
Beam energy on target [GeV]	100	4	5	1	8	20	500
Beam current in bunch train [mA]	3	20	40	26	9	5	9
Pulse duty factor [%]	100	0.2	2.0	6.0	0.5	0.7	0.5
Acc. gradient E_a = voltage gain / active length [MV/m]	6	25	25	18	32	24	31.5
E_p/E_a	2.3	2.0	2.0	2.1	2.0	2.0	2
B_p/E_a [mT/MV/m]	3.9	4.0	4.0	4.6	4.3	4.3	4.3
Operating temperature [K]	**4.5**	**2.0**	**2.0**	**2.1**	**2.0**	**2.0**	**2.0**
Unloaded Q-factor [10^{10}] @ nominal gradient	0.32	1	1	0.5	1	1	1
Dissipated power per cavity at nominal gradient [W]	**70**	**0.3**	**2.5**	**6.1**	**0.5**	**0.4**	**0.5**
Active length of cavity [m]	1.7	1.07	1.07	0.91	1.04	1.04	1.04
Max. power per cavity [MW]	0.06	0.5	1.1	0.4	0.3	0.1	0.3
Bunch repetition spectrum [MHz]	0.044	352	352	403	323	5	3
Number of cells per cavity	4	5	5	6	9	9	9

Choice of operating temperature and frequency

Remarks concerning cryostat



Comments:

The LEP cryostat could reliably be operated under CW conditions with beam and in pulsed conditions without beam in the present LHC tunnel environment (1.4 % slope).

It is worth noting that the lHe tank, the gas openings, and gHe collector were relatively small.

Pulsed operation: The thermal diffusivity $\kappa = \lambda/(c \cdot \rho)$ is such that it takes ~1 ms before the temperature pulse arrives at the niobium helium interface => advantage compared to CW operation.

This cryostat was tested under pulsed conditions with beam in the CERN SPS.

Concluding remarks

- β **< 1** cavities are inherently lower in gradient, compared to β = 1 cavities, because of
  - larger radial field increase
  - lower acceleration efficiency (transit time factor).

  If corrected for these two effects, performances are similar.
- **Simulation of Q(Ea)** by taking into account the deterministic performance parameters -
  - such as critical magnetic fields and heat transport through niobium wall and across Nb-He interface -

  predicts possible operation at acc. gradients of **25 MV/m** and more at all lHe temperatures, with a smaller margin at 1408 MHz and 4.5 K.
- A residual surface resistance corresponding to a **Q-value of 10^{10}** at the operating gradient presents a challenge (because of lacking knowledge of the causes).
- Test results from **outside labs** show that acc. gradients of **16 – 23 MV/m** (β = 1 cavities) for a **production yield of 90 %** are possible.
  Higher gradients (**20 – 30 MV/m**) are possible at the expense of **a lower production yield (~ 50%)**.
  Electro-polished and baked 1.3 GHz **mono-cell and 9-cell** cavities exhibit no significant difference in yield.
- The power consumption for the **high power SPL** is dominated by RF. It has the largest grid to beam power transfer efficiency (~ 24 %) at **2.5 K and 1.4 GHz**.
- The power consumption for the **low power SPL** is dominated by cryogenics. The grid to beam power transfer efficiency depends only weakly on the frequency and increases with temperature (2 – 4 %).
- **Power dissipation per cavity** in the SPL in pulsed operation is by **1 – 2 orders of magnitude smaller than for the LEP cavities** in CW operation. Therefore, design considerations for the LEP cryostat could provide valuable guidelines in addition to other designs.
  The temperature increase at the Nb-He interface is significantly reduced compared to CW for **pulsed operation** (< 1 msec pulse length).