Reach of NC and SC Technologies, 50 … 100 … 200 MV/m?

Erk JENSEN, CERN

June 2013

EuCARD'13

EuCARD is co-funded by the European Commission within the Framework Programme 7 under Grant Agreement no 227579.

Disclaimer

I was asked to give this presentation…

…because I'm **not** an expert!

… so don't expect too much,

I'll try and stay basic.

The work is from others,

the conclusions are mine

"Hey, why don't we just increase the limit?"

KEK Press Release Oct 2005

一般向けページ >> 研究者向けページ >> English Pages >>

Press Release

大学共同利用機関法人 KEK 高エネルギー加速器研究機構

Top | Access | For Visitors | Map & Guide | Document | Site Map | Search

>Top >PressRelease >ILC

last update:05/10/07

Press Release

KEK pushes superconducting cavity to work at its theoretical limit

Oct 14, 2005
High Energy Accelerator Research Organization (KEK)

Team of accelerator physicists led by associate professor Kenji Saito, High Energy Accelerator Research Organization (KEK), successfully achieved 52.3 MV/m field gradient on Niobium superconducting accelerator cavity. This gradient is an equivalent to connecting 35 million AA battery cells in series into one meter.

The high gradient superconducting cavity is one of the most vital components in designing the next generation high energy accelerators such as the International Linear Collider (ILC). Existing superconducting cavities, such as the ones developed by DESY, used to achieve 41 MV/m. Saito's group tested two types of single-cell cavities designed based on present understanding of the nature of the surface field limitation. KEK also contributed with its surface cleaning technique with ultra-high pressure water cleaning for perfecting the surface of the cavity, which is originally developed for KEK B-factory.

The two types of cavities are: the re-entrant shape (RE) figure 1 (left), designed and manufactured by Cornell University group led by Professor Hasan Padamsee, and the low-loss shape (LL), designed in collaboration by KEK, JLab and DESY, and manufactured by KEK Mechanical Engineering Center, figure 1(right). At the liquid helium temperature (2 K), the RE shape achieved the field gradient 52.3 MV/m at Qo = 0.97 x 10^{10}, which the LL shape achieved 47.3 MV/m at Qo = 1.13 x 10^{10} (Fig. 1). These values are the world records, and considered to be their theoretical limits with these cavity shapes.

SC: The present world record?

Proceedings of 2005 Particle Accelerator Conference, Knoxville, Tennessee

DESIGN OF A LOW LOSS SRF CAVITY FOR THE ILC

J. Sekutowicz, DESY, 22607 Hamburg, Germany
K. Ko, L. Ge, L. Lee, Z. Li, C. Ng, G. Schussman, L. Xiao, SLAC, Menlo Park, 94025 California, USA
I. Gonin, T. Khabibouline, N. Solyak, FNAL, Batavia, 60510-0500 Illinois, USA
Y. Morozumi, K. Saito, KEK, Tsukuba, 305-0801, Japan
P. Kneisel, TJNAF (JLAB), Newport News, 23606 Virginia, USA

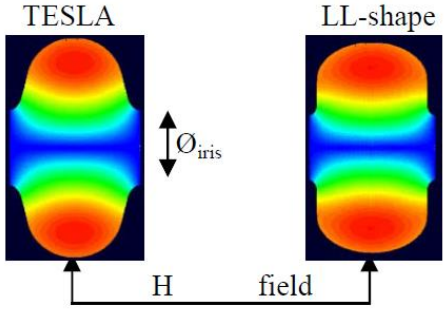


Figure 1: H contour in two shapes of inner cell.

Proceedings of 2005 Particle Accelerator Conference, Knoxville, Tennessee

WORLD RECORD ACCELERATING GRADIENT ACHIEVED IN A SUPERCONDUCTING NIOBIUM RF CAVITY*

R.L. Geng†, H. Padamsee, A. Seaman, V.D. Shemelin
LEPP, Cornell University, Ithaca, NY 14853, USA

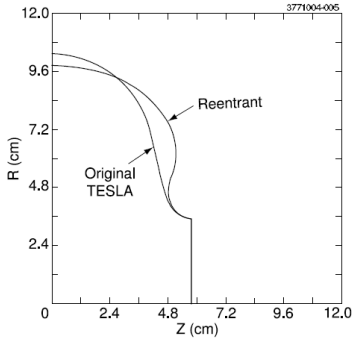
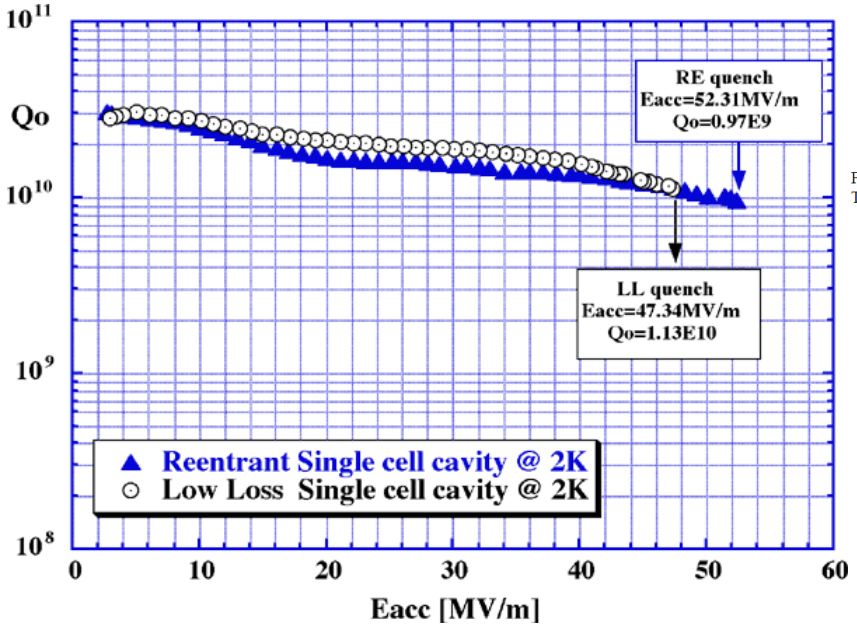
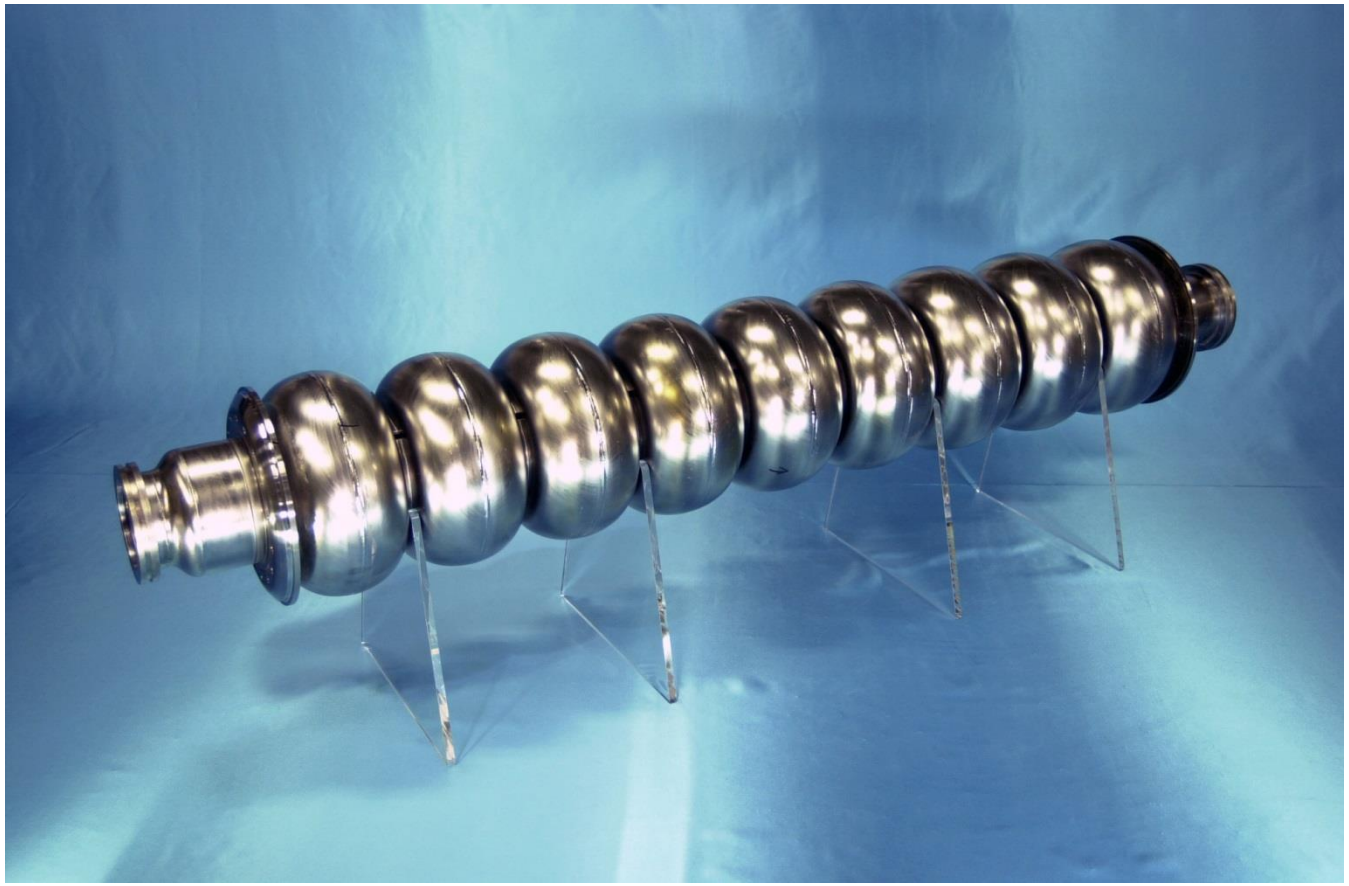


Figure 1: Half-cell contours of reentrant and original TESLA shape.



ILC 9-cell cavity

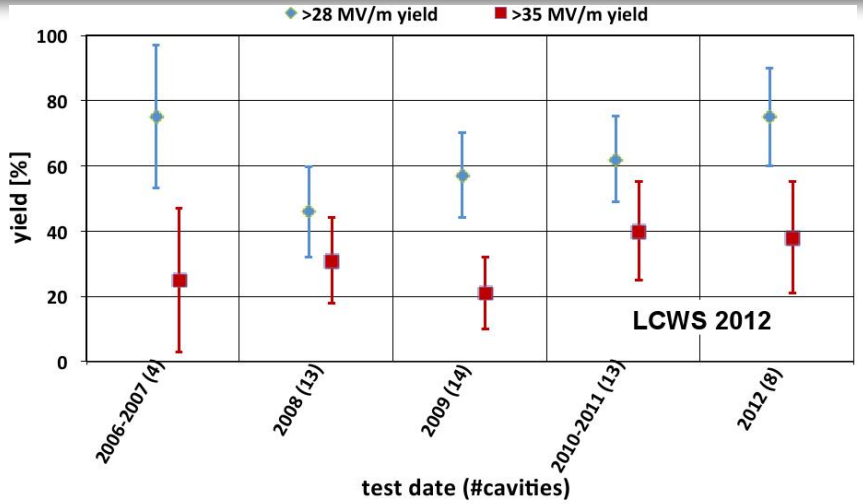


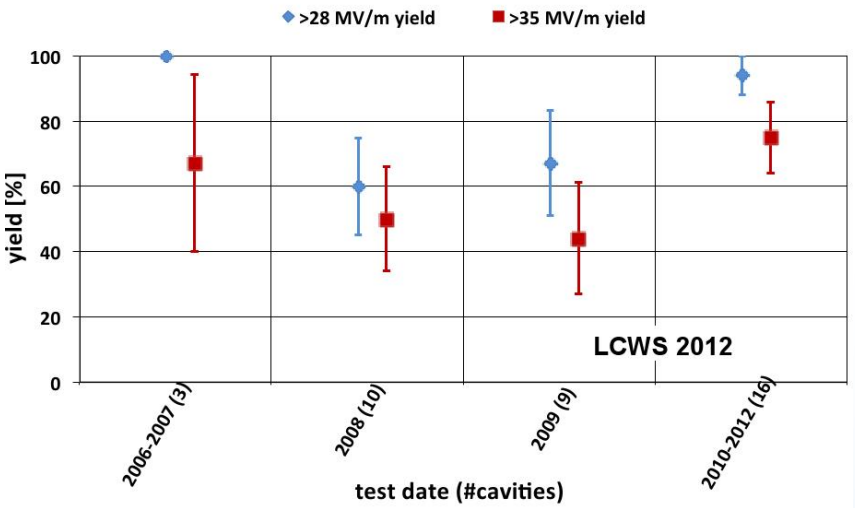
ILC RDR:
31.5 MV/m

ILC Newsline, Nov-2012

ILC reliable cavity production

- Red: percentage of cavities that reached > 35 MV/m
- Blue: percentage of cavities that reached > 28 MV/m
- Top and bottom: two different vendors.





NEWSLINE
THE NEWSLETTER OF THE LINEAR COLLIDER COMMUNITY

SC: Advances in technology

		WHY
Forming		
EB Welding		*Clean welding*
Ti purification		*RRR enhancement*
Chemical etching 100-200 µm	**BCP EP**	*Remove contamination and damage layer*
Annealing 800°C, 2h (or 600°C, 10h)		*Get rid of hydrogen*
Chemical etching 5-20 µm		*Remove diffusion layer (O, C, N)*
Specific rinsing		*e.g. remove S particles due to EP*
High pressure rinsing (HPR)		*Get rid of dust particles*
Assembling		*Ancillaries : antennas, couplers , vacuum ports…*
Baking, 120°C, 48h		*Decrease high field losses (Q-drop)*
Post processing		*Get rid of "re-contamination" ?*
Test RF		*Cavity's performance*
He processing, HPP		*Decrease field emission*

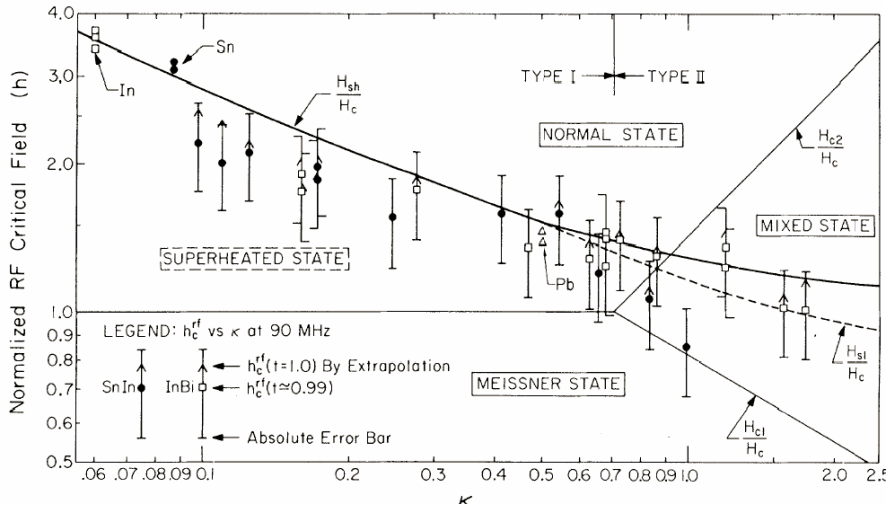
C. Antoine: CAS SC 2013

Photos: Rongli Geng

Other superconductors?

Material	$T_c[K]$	$H_c(0)[\mathrm{T}]$	$H_{c1}(0)[\mathrm{T}]$	$H_{c2}[\mathrm{T}]$	$\lambda_L[\mathrm{nm}]$
Pb	*7.2*	*0.08*			*48*
Nb	*9.2*	*0.2*	***0.17***	*0.4*	*40*
NbN	*16.2*	*0.23*	*0.02*	*15*	*200*
NbTiN	*16.5*		*0.03*		*151*
Nb_3Sn	*18.3*	*0.54*	*0.05*	*30*	*85*
MgB_2	*40*	*0.43*	*0.03*	*3.5*	*140*
YBCO	*93*	*1.4*	*0.01*	*100*	*150*

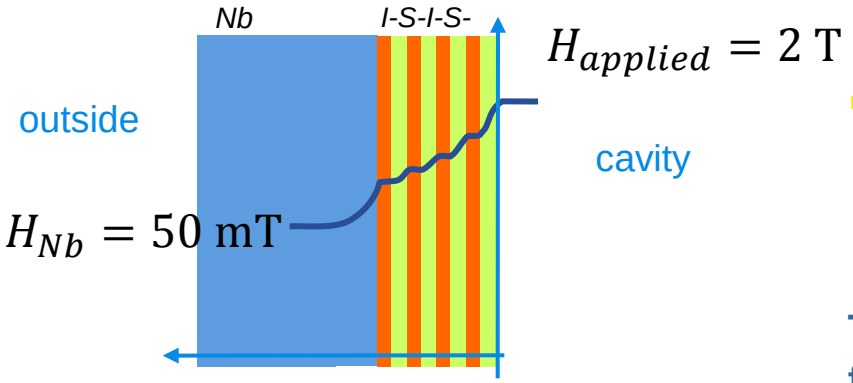
Gurevich, 2007,
C. Antoine: CAS SC 2013



- Nb favoured for RF (largest H_{c1}).
- It would be great to use the superheated state for RF – limited by **fast vortex penetration**.
- Interesting – should be studied!
- If solved, 100 MV/m are in reach!

Multilayers (Gurevich, 2006)

How to delay vortex penetration?



$$H_{Nb} = H_{applied}\, e^{-\frac{N\,d}{\lambda}}$$

- **Keep Nb, but shield surface from RF field to prevent vertex penetration**
- **Use nanometric films ($w\,d < \lambda$) of higher T_c superconductor.**
- **Example, NbN: $\xi = 5$ nm, $\lambda = 200$ nm, 20 nm film:**

$$H_{c1} = 4.2 \text{ T}$$

This is a very promising increase of a factor 200 !!!!

- **Similar improvement to be expected from MgB_2 or Nb_3Sn!**

C. Antoine: CAS SC 2013

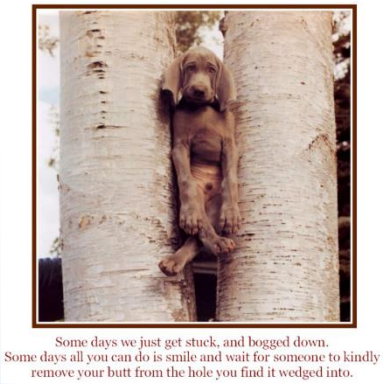
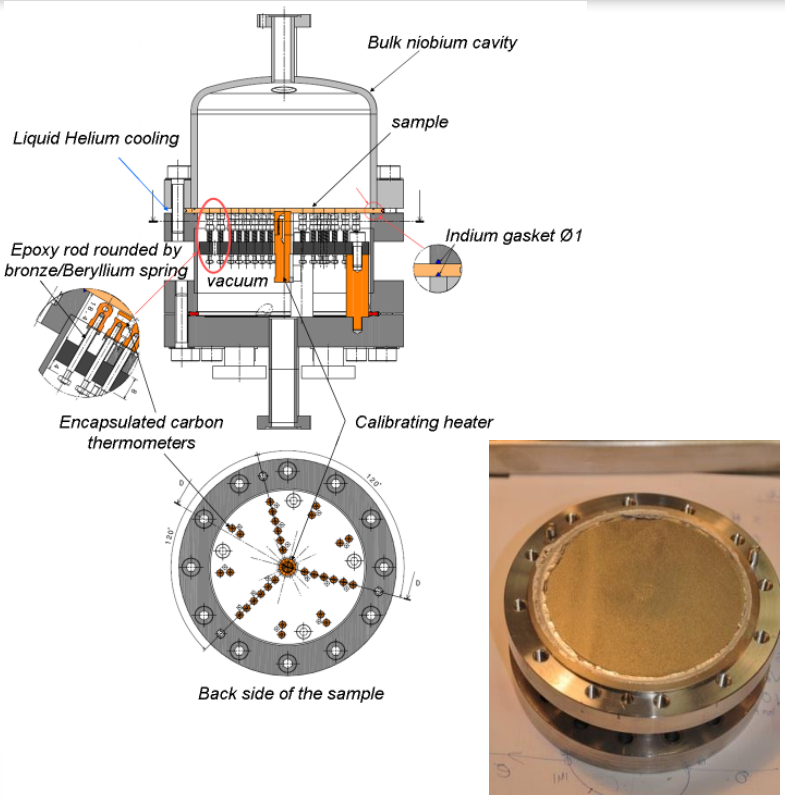
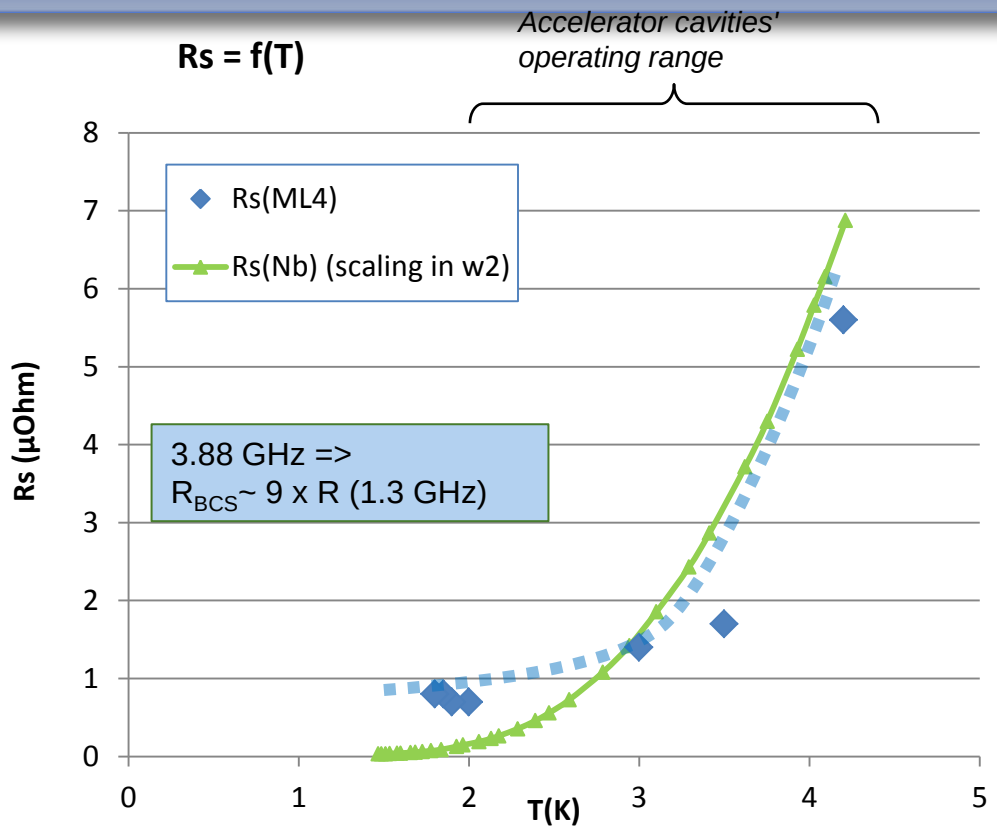


Image from Gurevich's SRF2007 presentation

Multilayers – 1st RF tests, 3.9 GHz





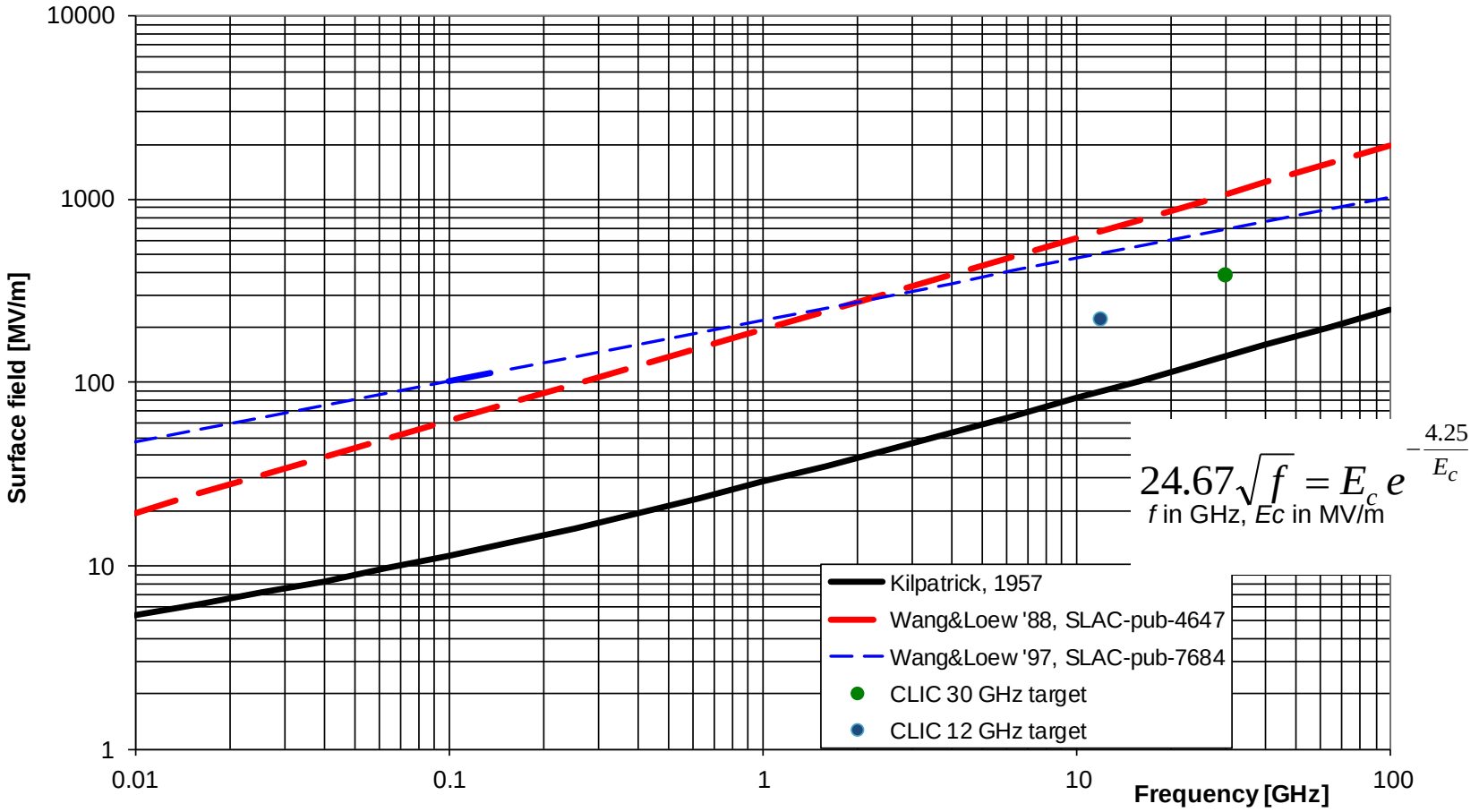
- Comparison is done with a high performance 1.3 GHz Nb cavity (scaled with ω^2)
- Indium gasket presents some defects measured with thermometric map => extra RF losses
- Residual resistance comes from NbN + bulk Nb substrate + indium gasket. Further investigations needed.

C. Antoine: CAS SC 2013

Conclusion SC

- **Tremendous progress has been made with Nb cavities!**
- **ILC – the state of the art!**
  - Single cell – reached 53 MV/m
  - Production aims at 31.5 MV/m
- **The limit is the surface magnetic field – Nb is now used near this limit**
- **performance of SC cavities limited by surface quality!**
- **H_{SH} looks interesting, but is hard to reach in real cavities.**
- **Multilayers have the potential to extend the reach significantly**
  - … but this technology is not ready yet and needs study!

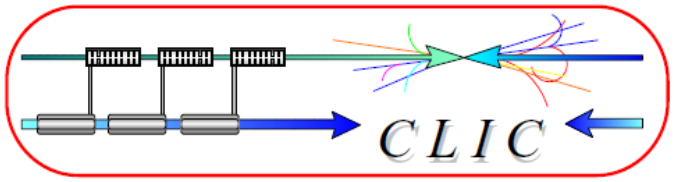
NC structures "classical" limit



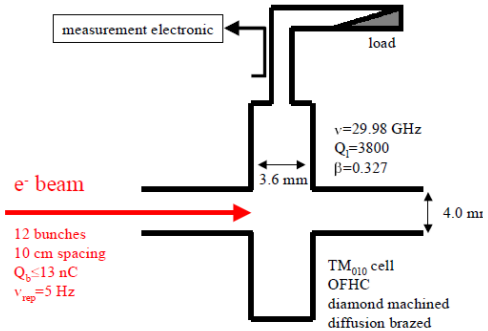
Normal conducting, on Cu

These limits are now known to be wrong – better models exist

NC – state of the art, 2000



CLIC Note 431

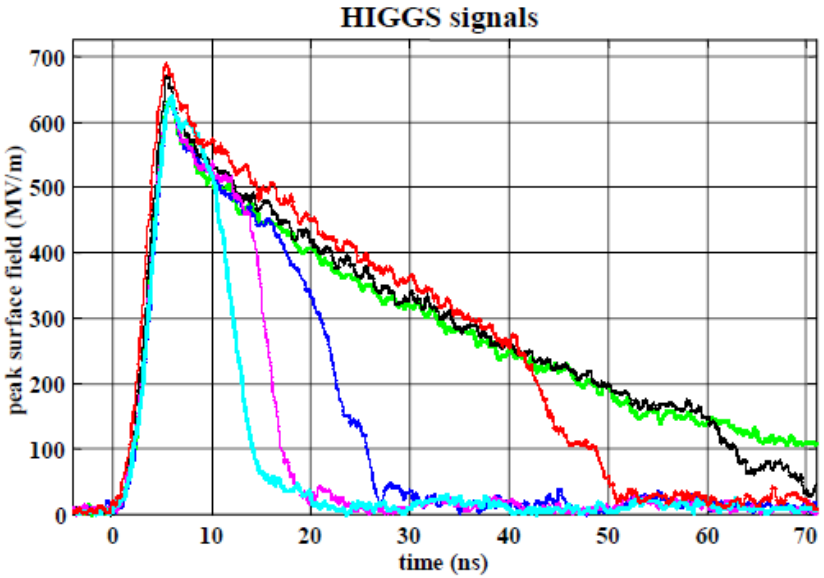


peak surface field	observations	surface temperature rise (estimated)
540 MV/m	no break downs	44 K
590 MV/m	onset of breakdowns	53 K
750 MV/m	break downs on every pulse, few ns after max. E(t)	85 K

Delayed RF breakdown in a microwave cavity

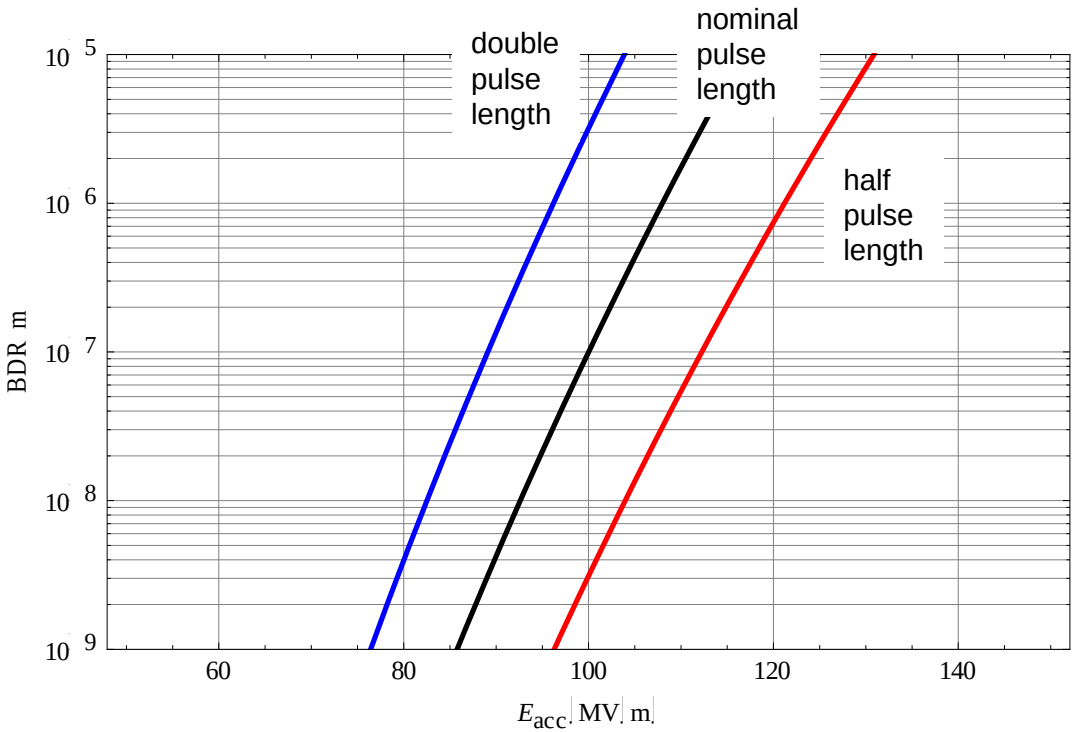
G. Geschonke and W. Schnell

Geneva, Switzerland
3 April 2000



… but: too many sparks

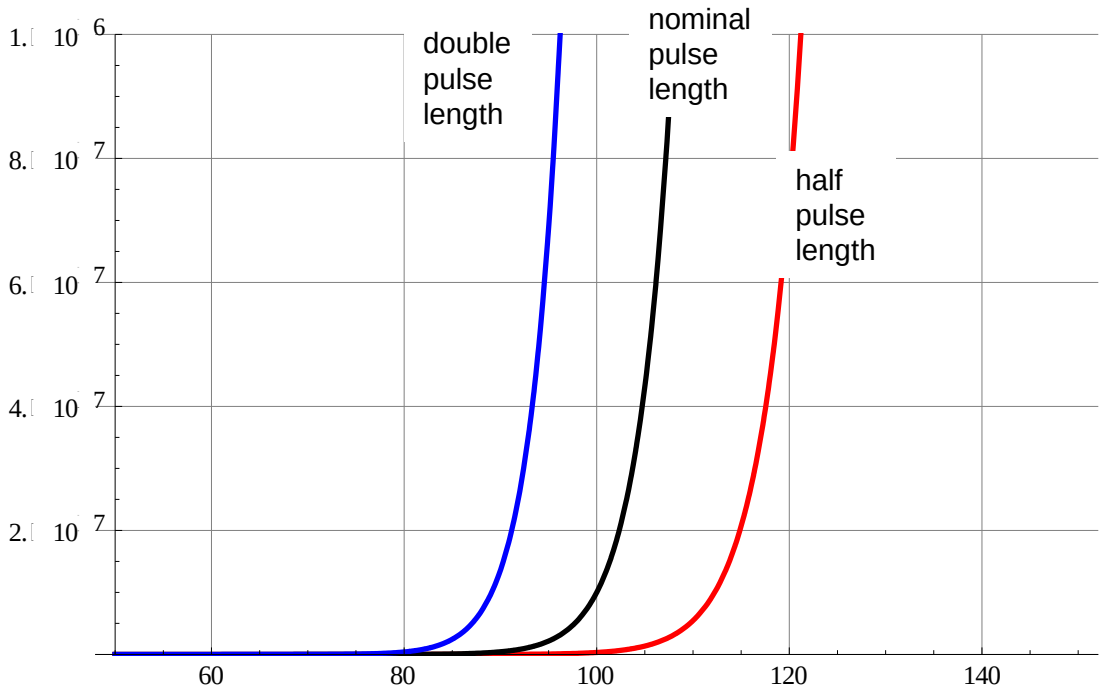
Observed: $BDR \propto E^{30}\,\tau^{5}$



… this is quite a hard limit:

… quite a hard limit!

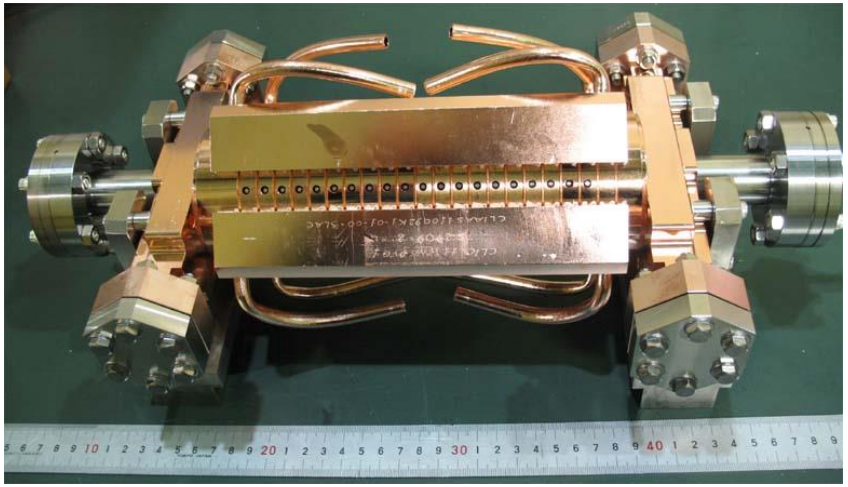
Observed: $BDR \propto E^{30}\,\tau^{5}$



The rapid increase of the breakdown rate indicates some **drastic** changes near the surface!

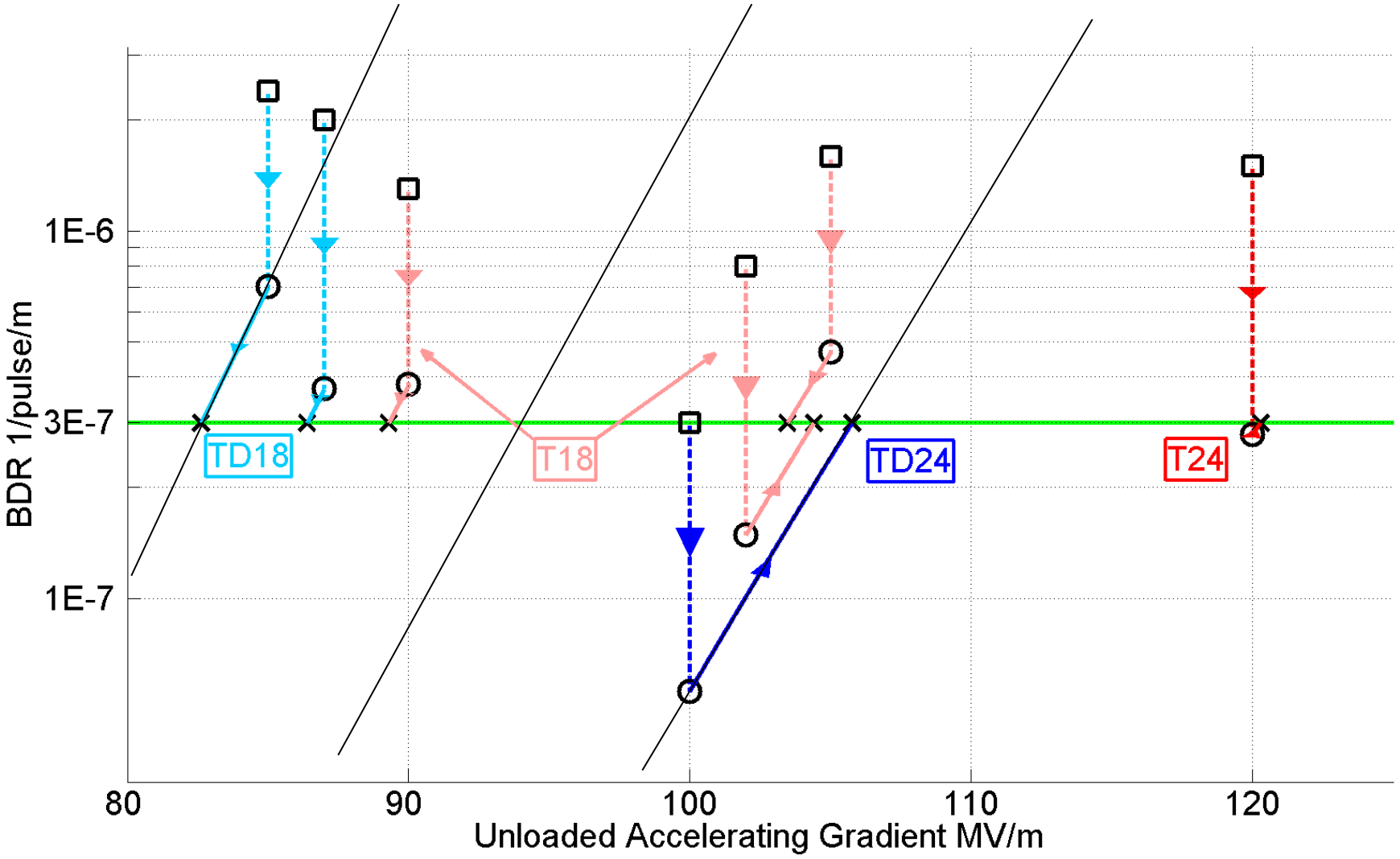
CLIC accelerating structures

- Target 100 MV/m accelerating gradient
- This target is reached – at the correct BDR and with correct pulse length!



W. Wuensch: 7th LC School, 2012

Achieved accelerating gradients

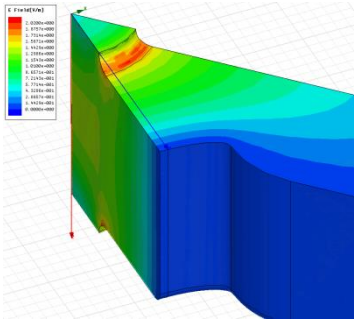


W. Wuensch: 7th LC School, 2012

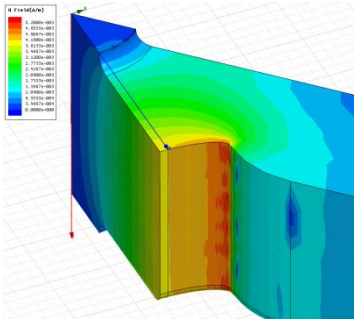
What limits the acc. gradient?

- Electric surface field (Field emission, CLIC: 230 MV/m)
- Ratio $E_{surface}/E_{acc}$, about 2.2 for CLIC
- Magnetic surface field (surface current density)
- Max. pulsed surface heating (CLIC: 45 K)
- Modified Poynting vector S_c

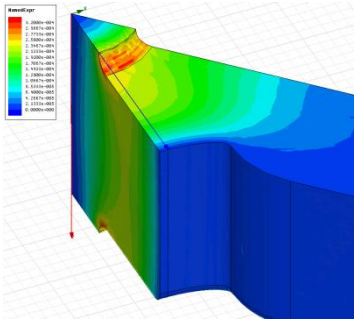
$E_{surface}/E_{acc}$



$H_{surface}/E_{acc}$



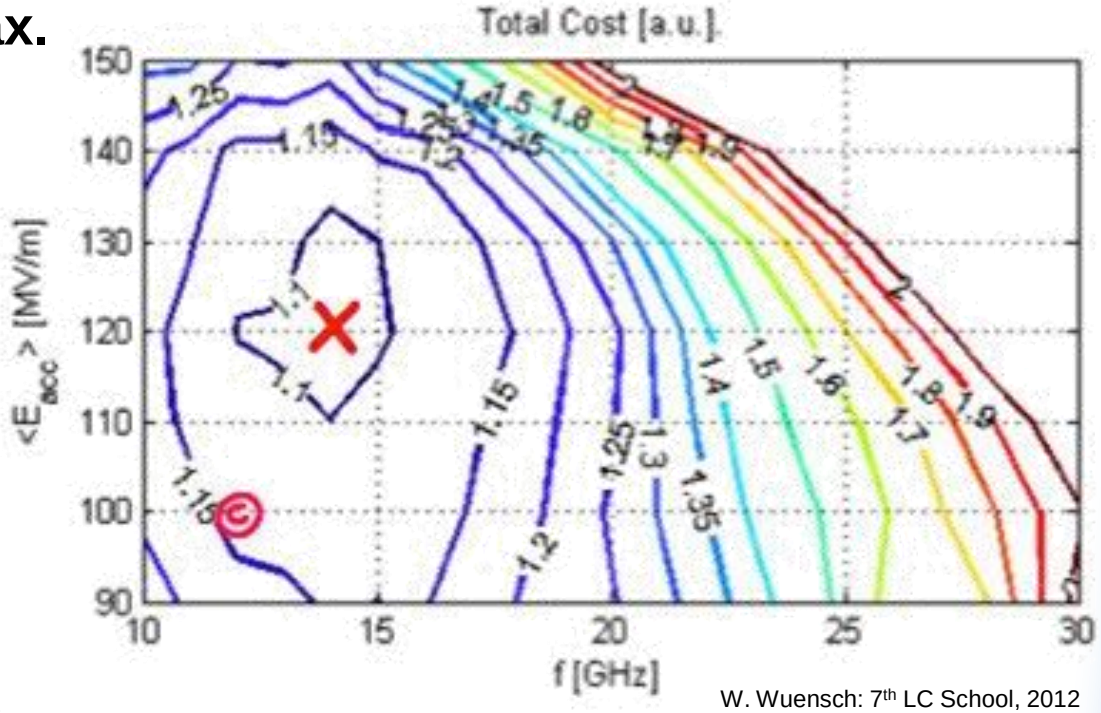
S_c



W. Wuensch: 7th LC School, 2012

This allows optimization

- **Define a figure of merit (FoM) to evaluate one given CLIC design/parameter set (here $FoM = -cost$)**
- **Define parameters to fully describe the design/parameter set**
  - e.g. gradient, frequency, phase advance, aperture, …
- **Define constraints (max. surface fields, ΔT, ...)**
- **Run optimization algorithm …**



W. Wuensch: 7th LC School, 2012

Overall CLIC optimization

$FoM = L_{bx}/N \cdot \eta$

BD

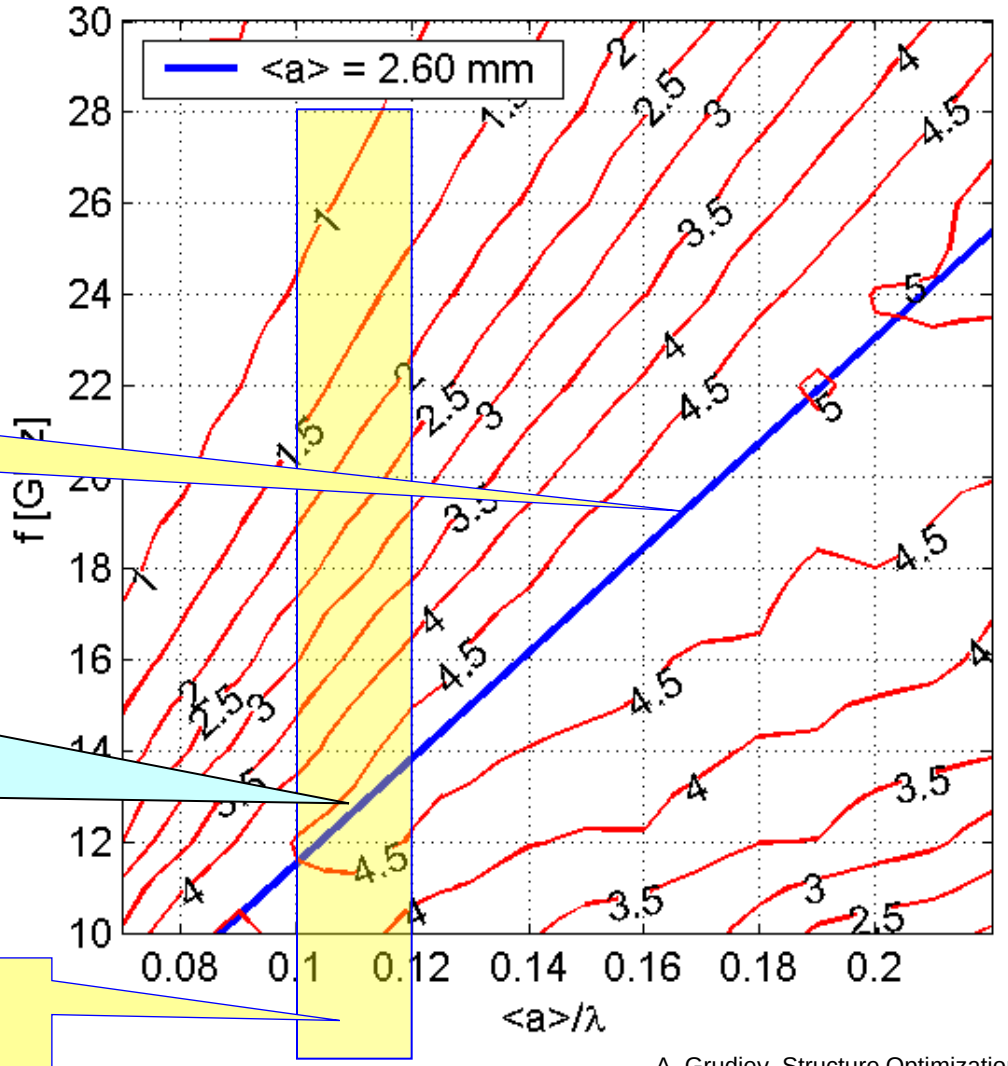
RF

From beam dynamics: optimum aperture <a> = 2.6 mm

Why X-band ?

Crossing gives optimum frequency

High-power RF optimum aperture: $\langle a \rangle/\lambda = 0.1 \ldots 0.12$

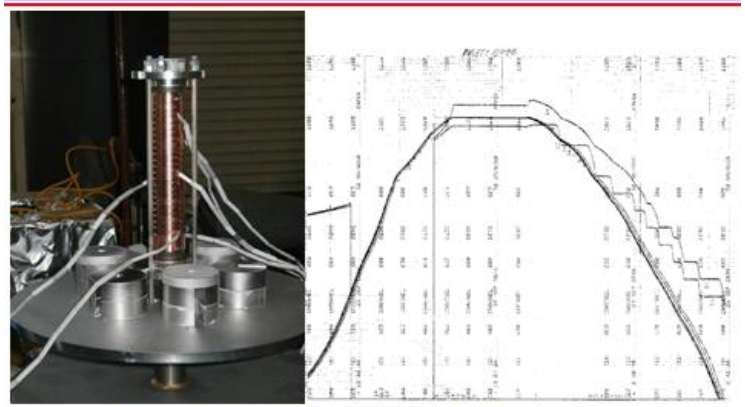


A. Grudiev, Structure Optimization

Materials/heat treatments

Disk stacking

Diffusion Bonding of T18_vg2.4_DISC



Pressure: 60 PSI (60 LB for this structure disks)

Holding for 1 hour at 1020° C

Vacuum Baking of T18_vg2.4_DISC

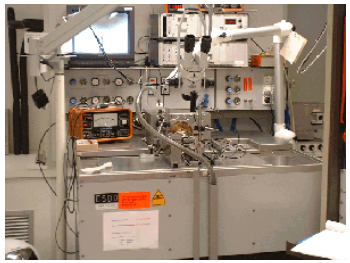
650° C

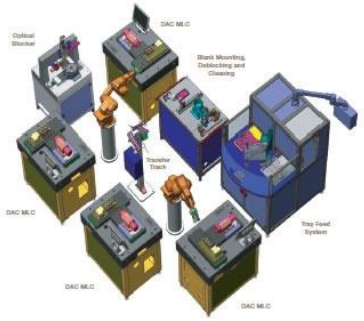
10 days

Evolution of high precision machining

Single point diamond turning

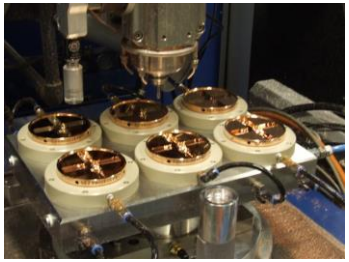
Up to the 1980's	1980's - 1990's	2000's - 2010's	Future ?
First machines at research institutes and universities	Start of industrialization • *Optical recording* • *contact lenses*	• *Larger machines* • *Multiple axis (X/Y/Z and C)*	• *Intelligent machines ?* • *Robotisation ?*



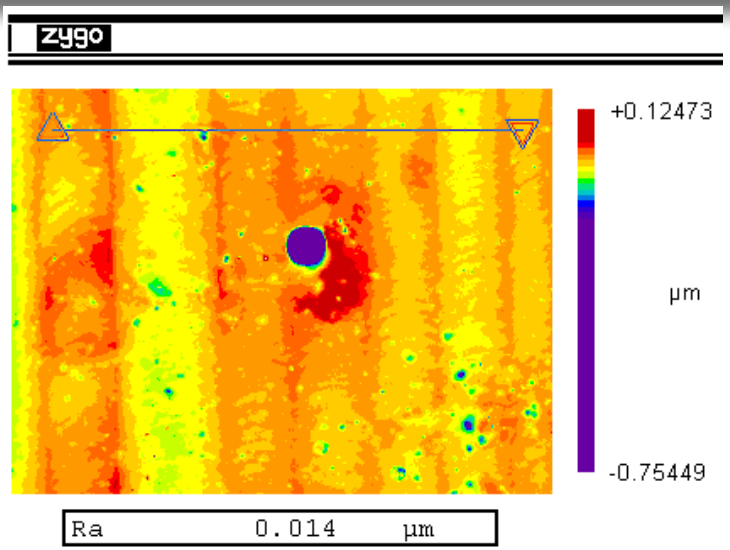


Ultra precision diamond milling *(lagging more than a decade behind on turning)*

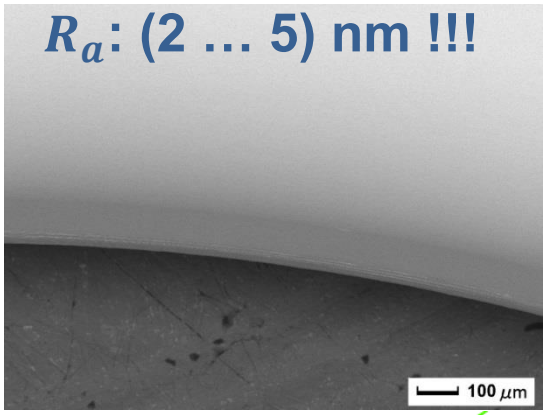
Up to the 1990's	1990's - 2000's	2010's	Future ?
Limited to fly cutting • *mirror optics* • *Laser scanner mirrors*	Milling as add-on on lathes • *Lens arrays* • *Intra ocular lenses*	First proto type machines • *Micro fluidics* • *Accelerator parts*	• *Pallet machining?* • *Robotisation ?*



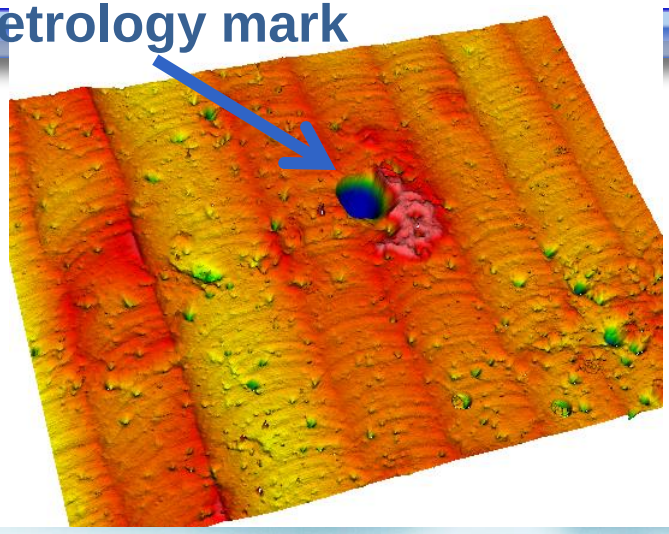
High precision machining, surface finish

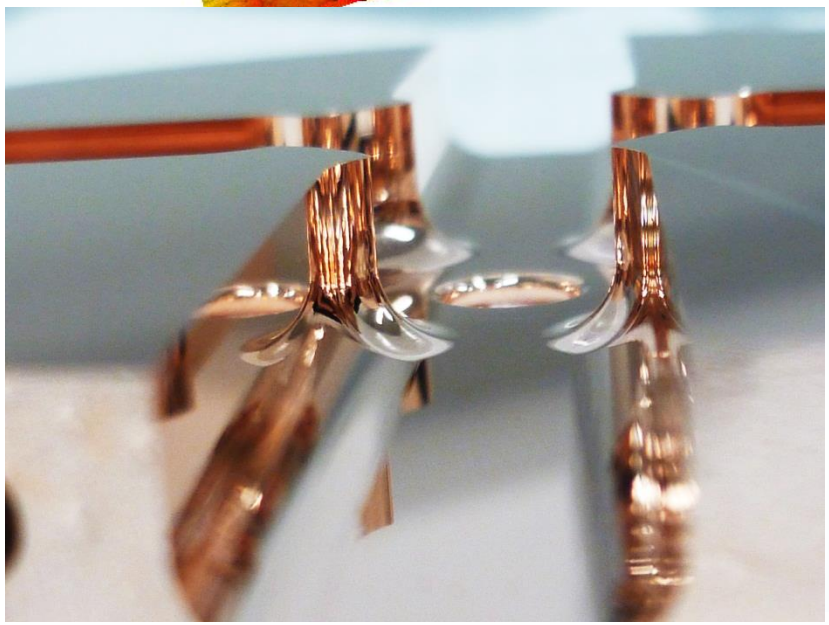


R_a: (2 … 5) nm !!!



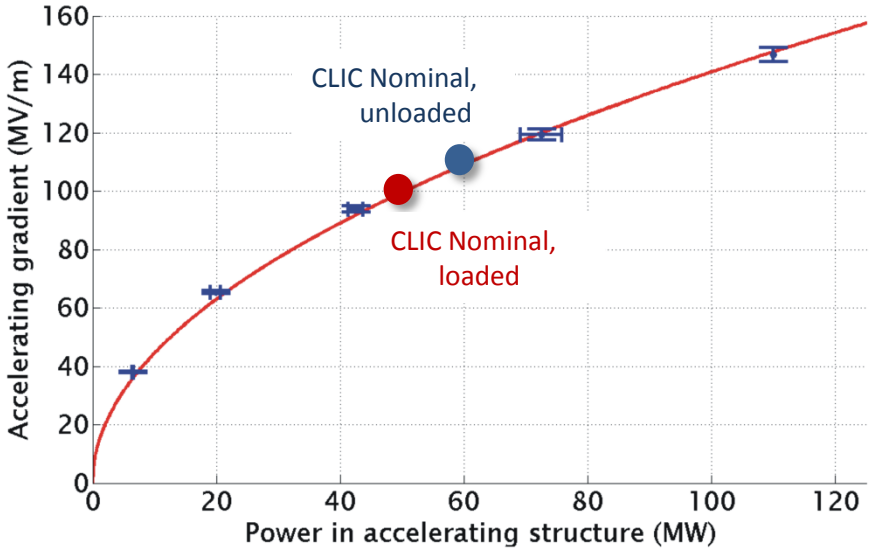
Metrology mark



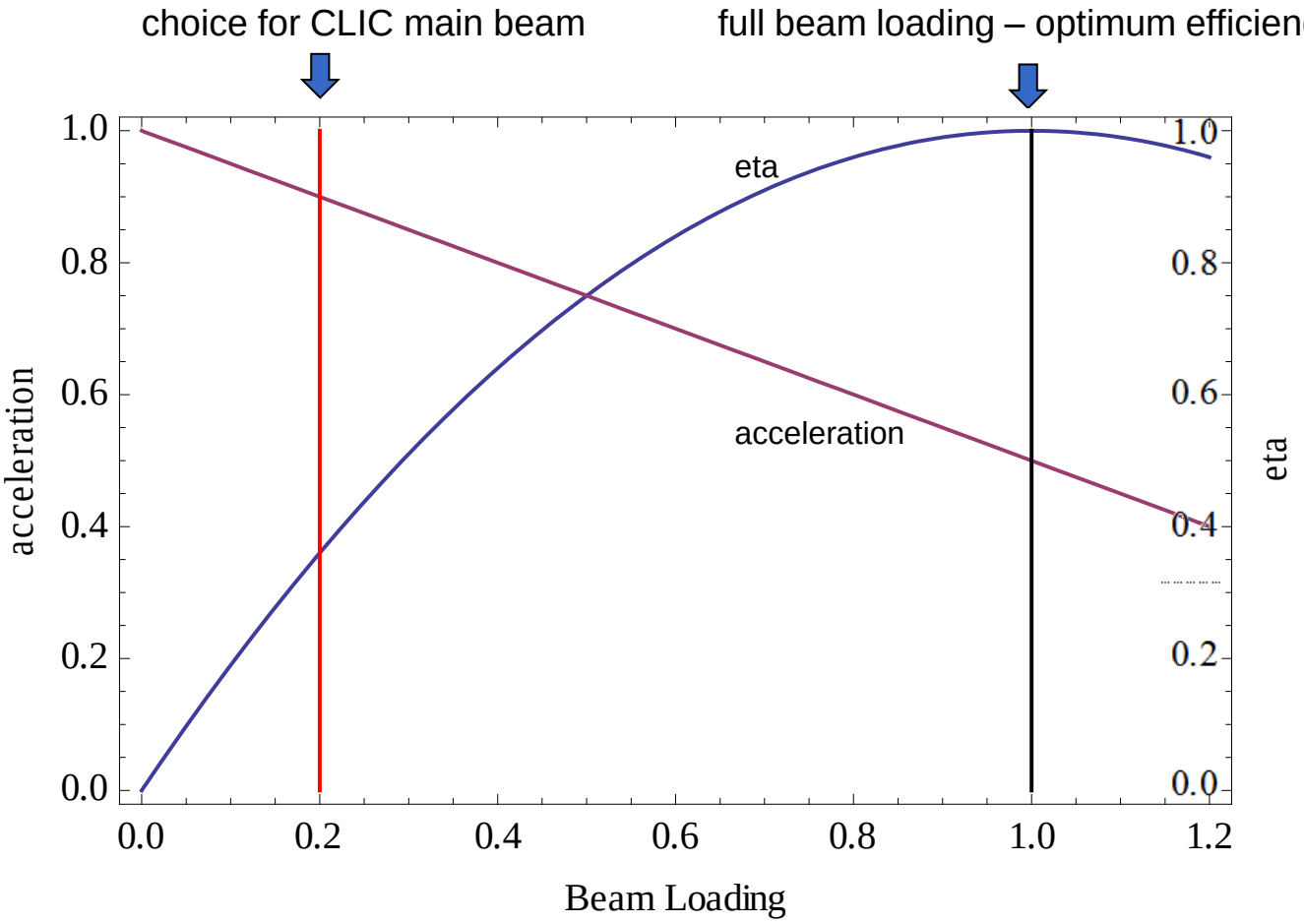


CLIC Power needs

Approximately: $60\ \frac{\mathrm{MW}}{22\ \mathrm{cm}} \left(\frac{E_{acc}}{100\ \mathrm{MV/m}}\right)^2$



Beam Loading – allows efficiency!



Conclusion NC

- **Tremendous progress has been made in material science, fabrication and joining techniques with NC accelerating structures.**
- **CLIC – the state of the art!**
  - The goal of 100 MV/m loaded gradient, with correct pulse length and BDR, has been demonstrated
  - In individual cells, 150 MV/m are regularly reached.
- **The breakdown rate is a very steep function of the field – an indication that *something drastic* happens near the metal surface when operating close to the limit**
- **The latter needs deeper study to find mitigation eventually!**

Conclusion

- The R&D programs for both NC and SC have triggered fantastic progress in technology, cutting edge fabrication techniques, material science, …
- Both technologies have a major impact on industry
- With present day technology, the reach for NC seems to be $< 150\ \mathrm{MV/m}$, limited by a sharp increase in BDR; for Nb based SC, the limit seems to be $< 50\ \mathrm{MV/m}$, limited by H_{c1}.
- To go beyond, the secret lies at the surface (and just beneath)!