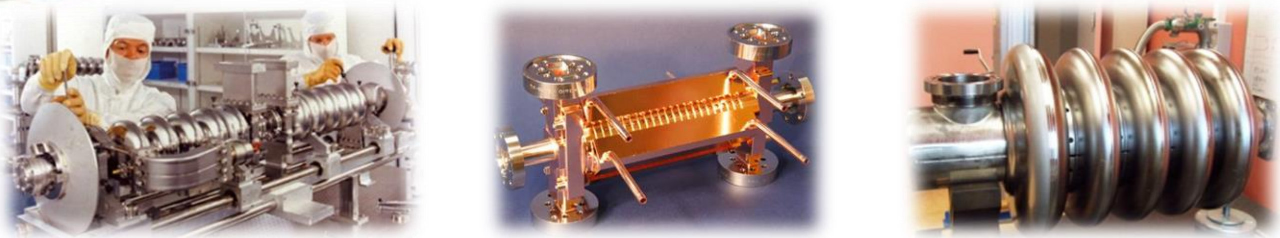
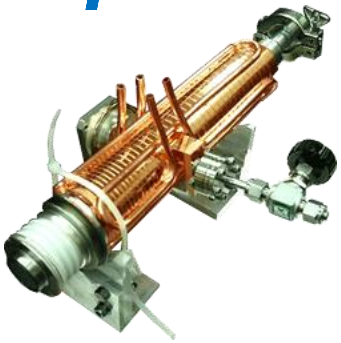


High(er) Accelerating Gradients

A. Wheelhouse
ASTeC, STFC Daresbury Laboratory

Advanced School on Accelerator Optimization at Royal Holloway University of London,
7th – 11th July 2014



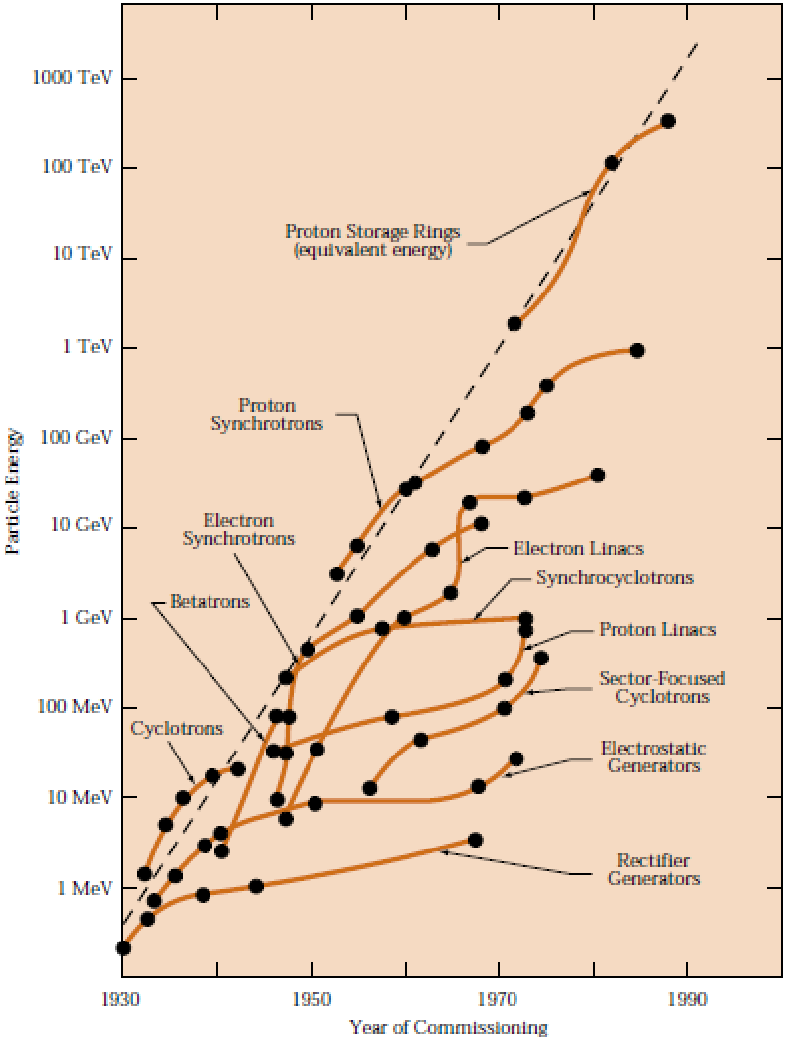
Outline

- Introduction
- Basic concepts
  - Superconducting RF cavities
  - Normal conducting RF cavities
- Gradient Limitations
- Current Challenges & R&D

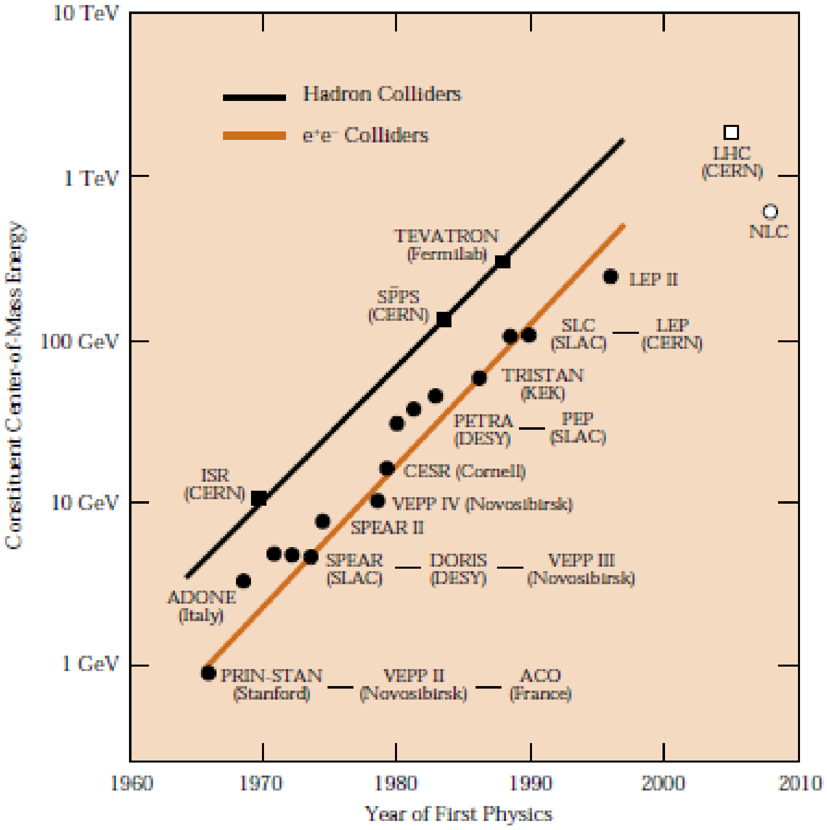
Introduction

Accelerator Evolution

Accelerator Evolution



Particle Colliders

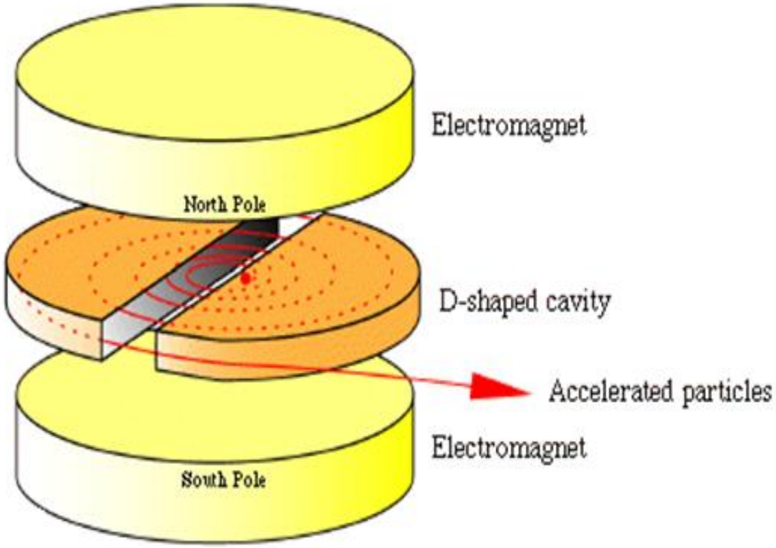


'The Evolution of Particle Accelerators and Colliders', W Panofski

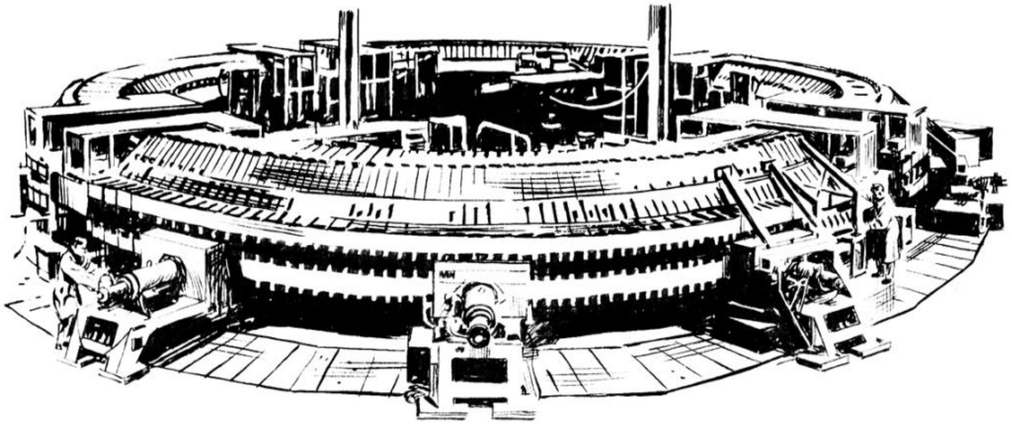
Accelerator Evolution

Early accelerators

Cyclotrons (1931 ➪)



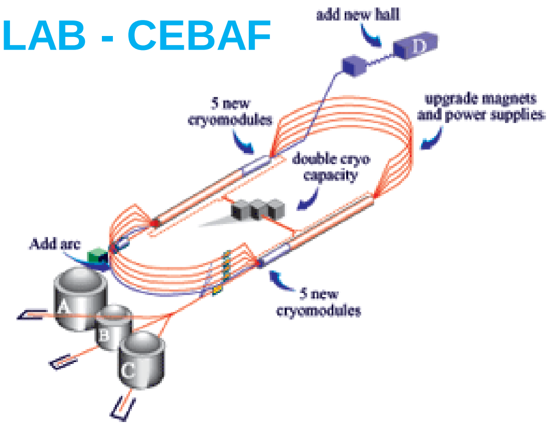
Synchrotrons (1953 ➪)



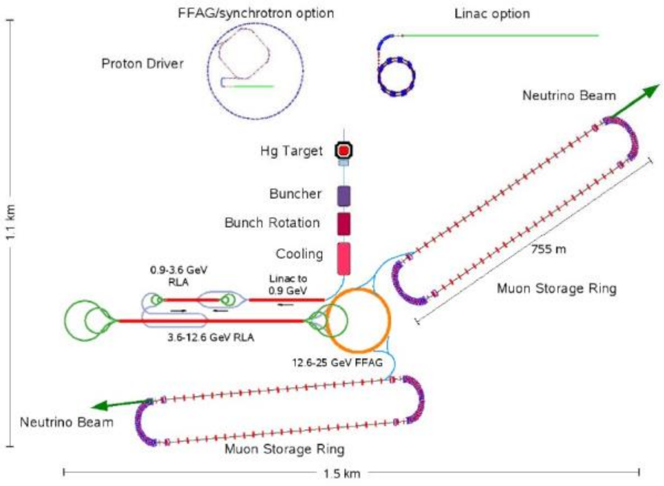
Cosmotron, Brookhaven National Laboratory (1953)

Accelerator Evolution

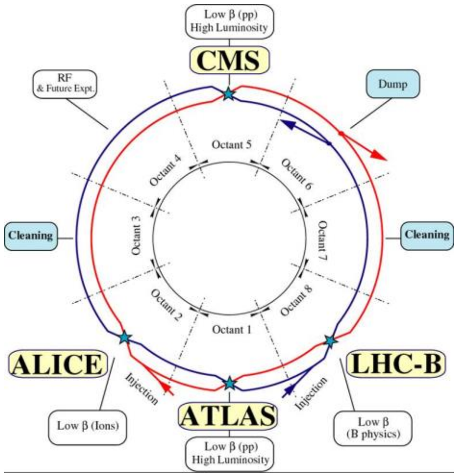
JLAB - CEBAF

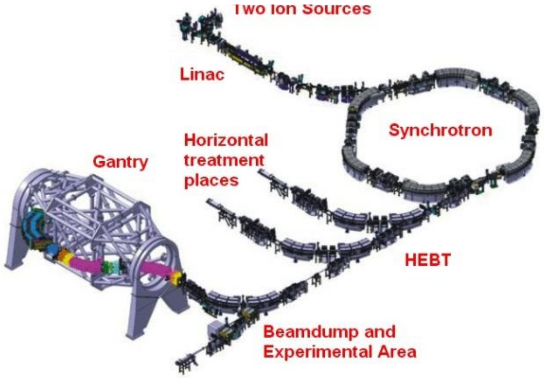


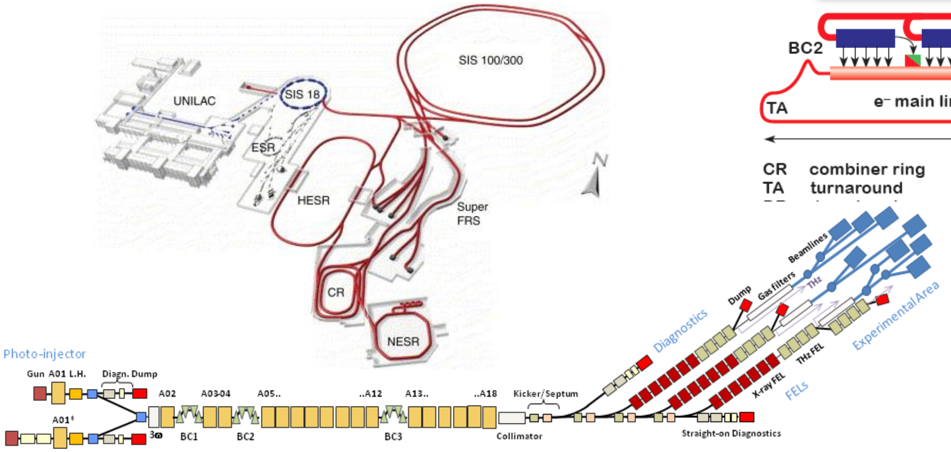
Neutrino Factory

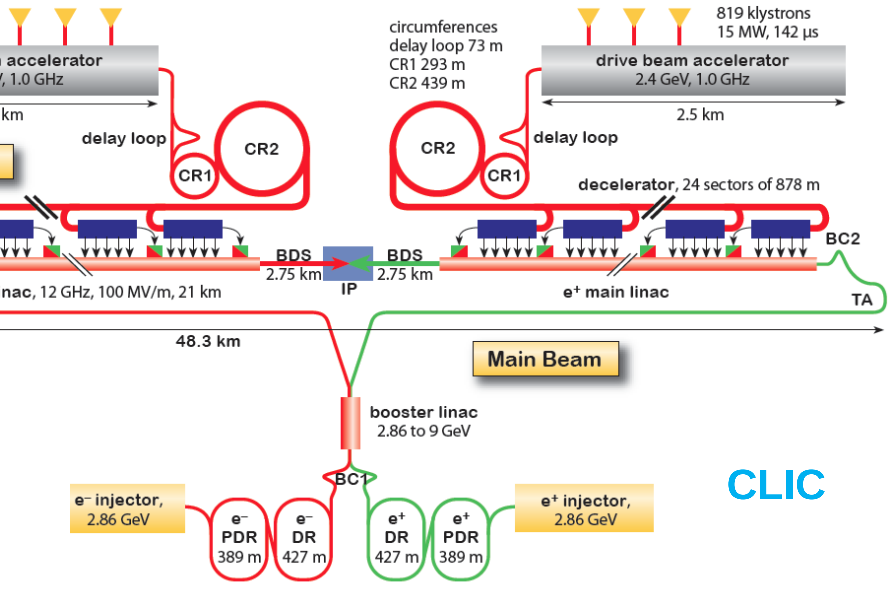


CERN - LHC









CLIC

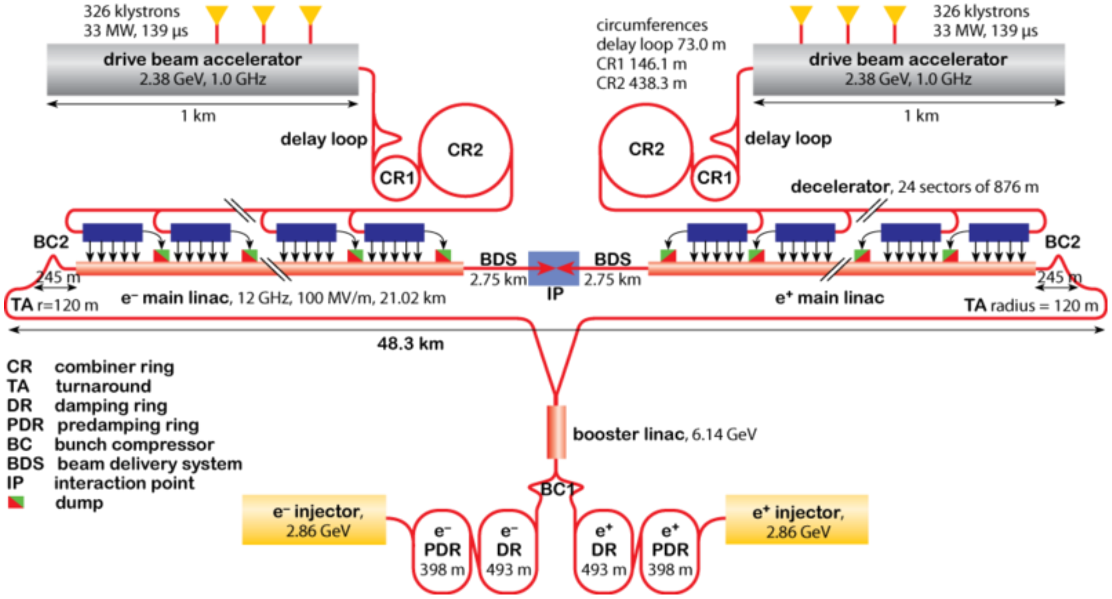
Optimization

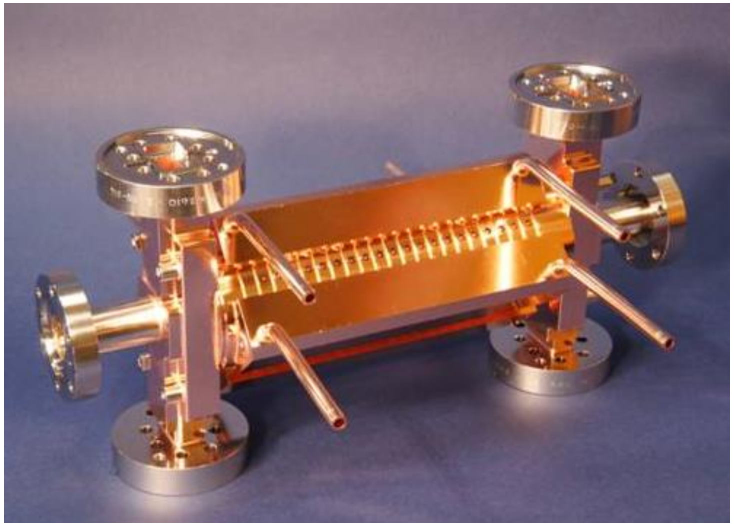
A Wheelhouse

RF Technology Requirements

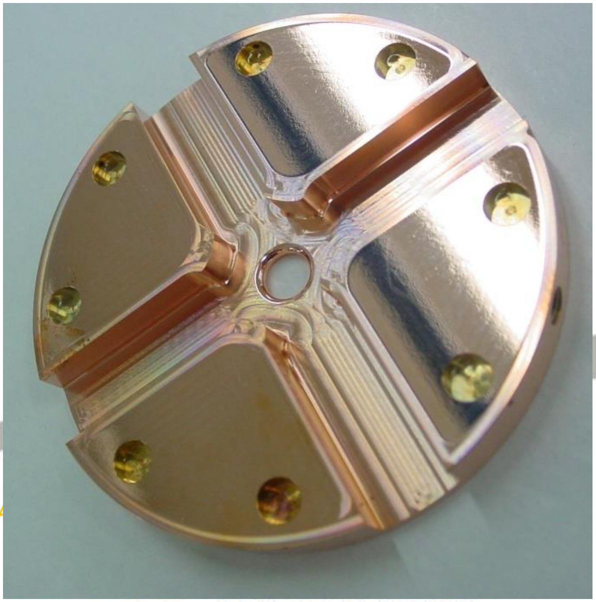
- Accelerating gradient is the energy gain per acceleration length
- To achieve higher beam energies
  - ⇨ Longer accelerators (linear)
    - Space and cost are issues
  - ⇨ Improvements in accelerating gradients
    - Technology limitations
- RF technology requirements:
  - – Operation at the required frequency
  - – Accelerate to the required voltage
  - – Suppress HOM instabilities
  - – Operate efficiently
  - – Deliver the required RF power to the beam
  - – Control amplitude and phase

Compact LInear Collider (CLIC@CERN)





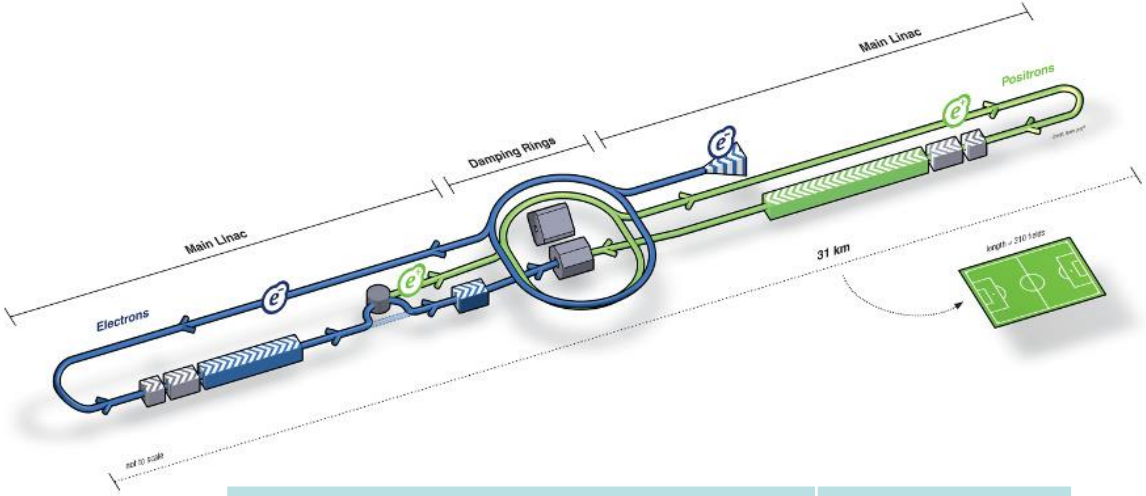
Parameter	Units
Length (km)	48.3
Physics Beam Energy (TeV)	3
RF Frequency (MHz)	12000
Number of RF Cavities	140000
Cavity Field (MV/m)	**100**
Q-Factor (bulk Cu)	44 x 10^3
Luminosity ($cm^{-2}s^{-1}$)	5.9 x 10^{34}

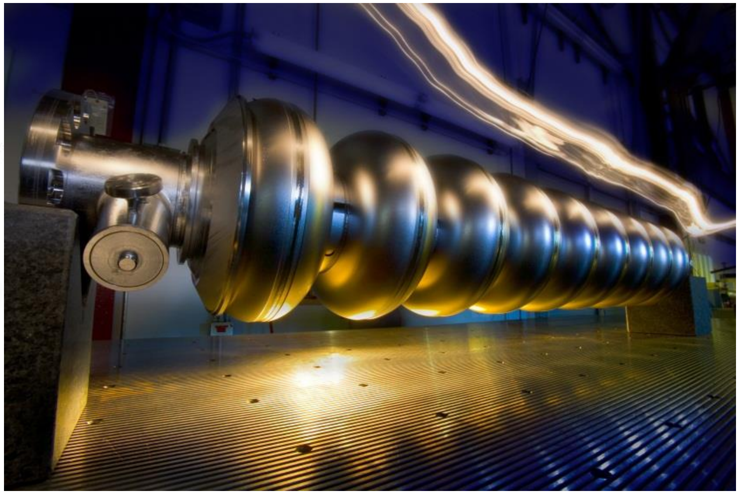


NC

http://home.web.cern.ch/about/accelerators/compact-linear-collider

International Linear Collider (ILC@Japan?)



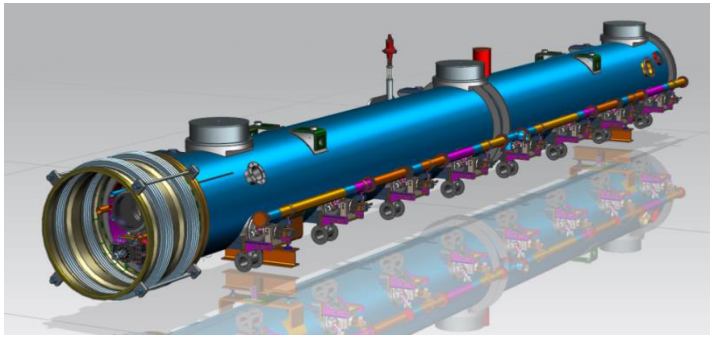


Parameter	Units
Length (km)	31
Physics Beam Energy (TeV)	0.5
RF Frequency (MHz)	1300
Number of RF Cavities	16000
Cavity Field (MV/m)	**31.5**
Q-Factor (bulk Nb)	1 x 10^{10}
RF Operating Temperature (K)	2
Luminosity ($cm^{-2}s^{-1}$)	2 x 10^{34}

SC

http://www.linearcollider.org/ILC

LCLS-II (@SLAC)



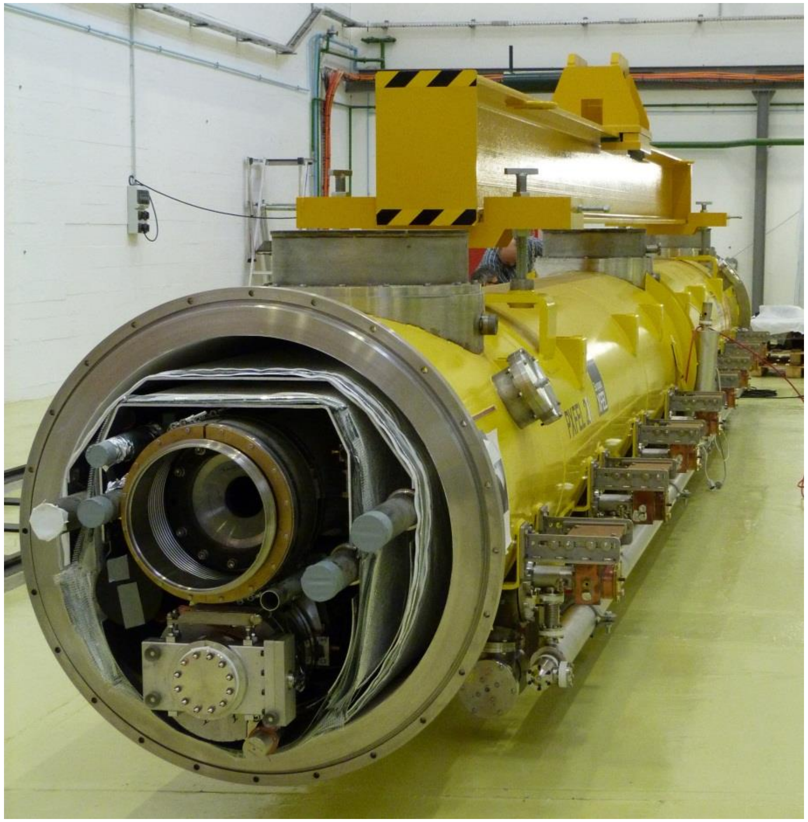
Commissioning planned for late 2019

Parameter	
RF Frequency (MHz)	1300
Operating Temperature (K)	2
Average Operating Gradient (MV/m)	**~16**
Average Q_o	$2.7\text{x}10^{10}$
Cavity Length (m)	1.038
R/Q (Ω, Ω/m)	1036, 998
HOM damped Q (Monopole & Dipole)	$\leq 10^7$
No. of Cavities per Cryomodule	8
RF Power per Cavity (kW)	6.3
Cavity Dynamic Load (W)	10
Cavity Amplitude Stability (%)	0.01
Cavity Phase Stability (º)	0.01

SC

https://portal.slac.stanford.edu/sites/lcls_public/lcls_ii/Pages/default.aspx

X-Ray Free Electron Laser (XFEL@DESY)



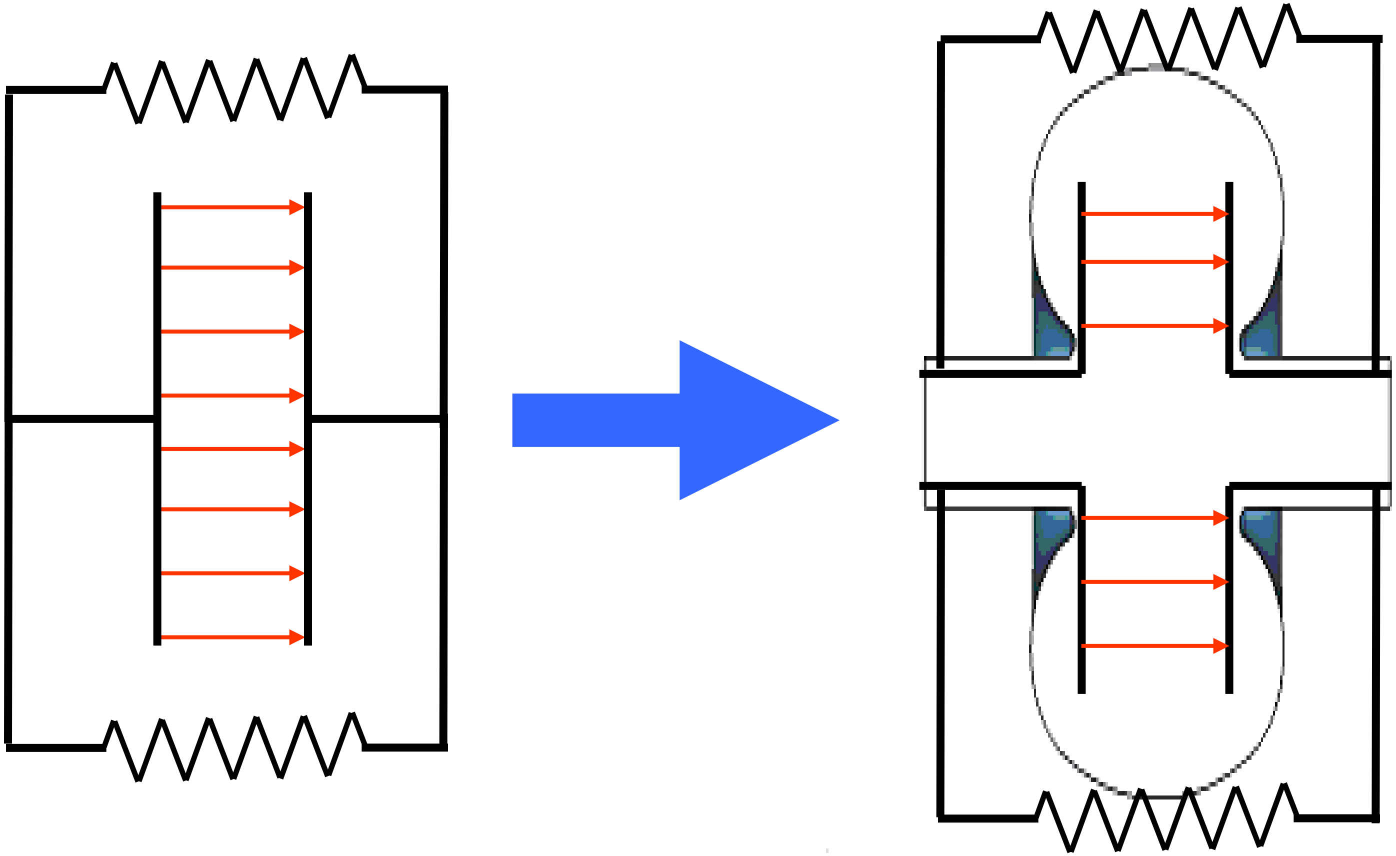
Total Length	3.4	km
Energy	17.5	GeV
Beam Current	5	mA
Accelerating Gradient	**23.6**	MV/m
Quality Factor Qo	10^{10}	
Repetition rate	10	Hz
Number of Cavities	824	
Number of Cryomodules	103	

SC

http://www.xfel.eu/

Basic Concepts

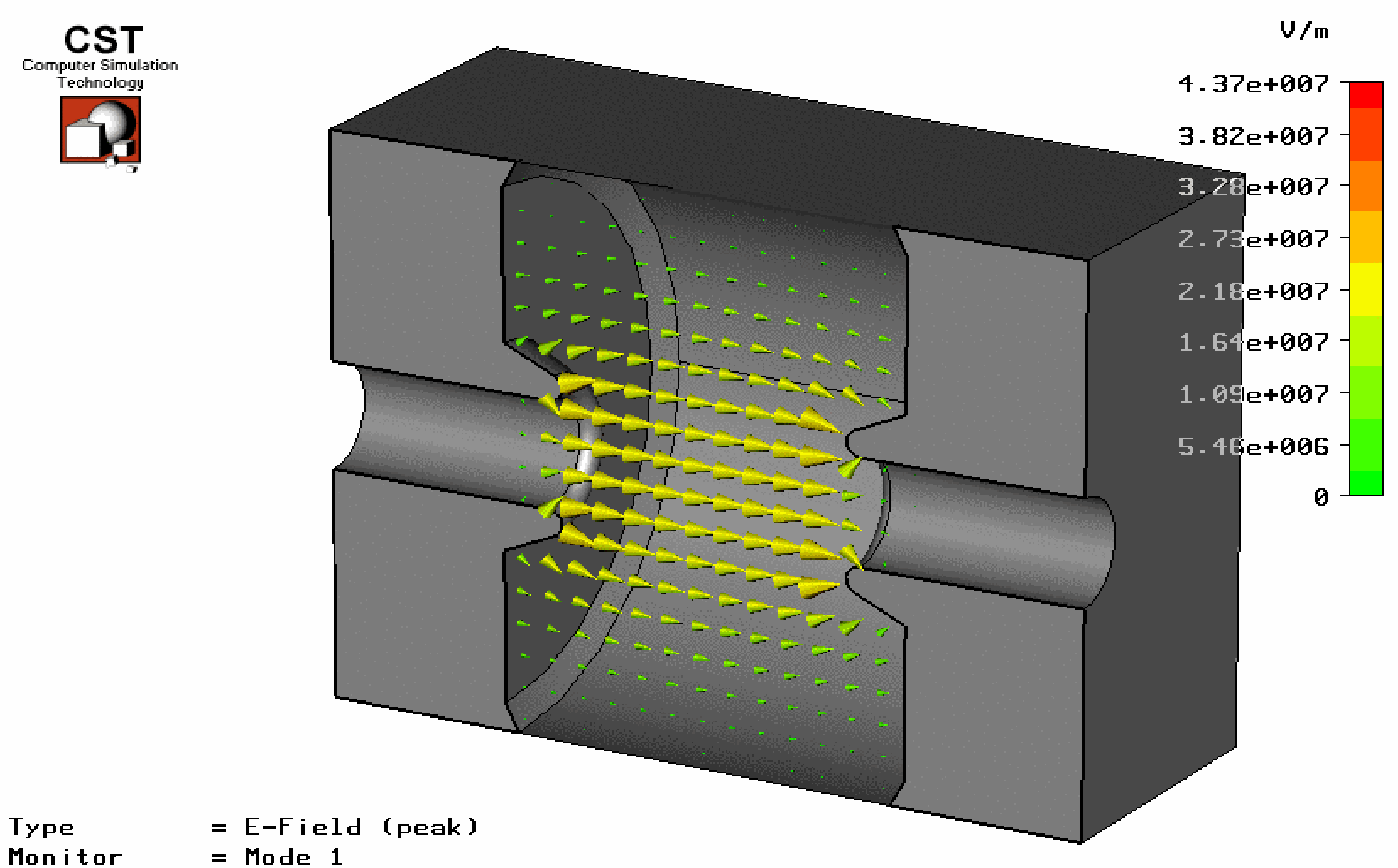
The RF Cavity



The resonant frequency is determined by:

$$f_0 = \frac{1}{2\pi\sqrt{LC}}$$

Accelerating Voltage, V_{acc}



```
Type          = E-Field (peak)
Monitor       = Mode 1
Plane at z    = 0
Frequency     = 1.28858
Phase         = 0 degrees
Maximum-2d    = 4.36809e+007 V/m at -41.0665 / 19.37 / -2.80202e-015
```

RF Technology Parameters

$$P_{diss} = \frac{V_{acc}^2}{R/_{Q} \, . \, G} \, . \, R_s$$

P_{diss} – Power dissipated in cavity wall
V_{acc} – Accelerating voltage
R/Q – Constant dependant on cell shape
G – Geometry constant
R_s – Surface resistance

Normal Conducting

$$R_s = \frac{1}{\sigma\delta} = \sqrt{\frac{\pi\mu_o\mu_r f}{\sigma}}$$

Typically several mΩ for OFE copper

Superconducting RF

$$R_s(BCS) = 2.10^4 \, \frac{1}{T} \left(\frac{f}{1.5}\right)^2 e^{-\frac{17.76}{T}}$$

Typically several nΩ for high purity Nb @ 2K.

δ = Skin depth (m)
σ = Conductivity (S/m)
μ_o = Free-space Permeability (H/m)
μ_r = Relative permeability (H/m)
f = Frequency (Hz)
T = Temperature (K)
W = Stored energy (J)
U_a = Effective voltage (V)

Q-Factor, Qo

Stored energy

$$Q_0 = \frac{\omega W}{P_c}$$

Power dissipated in cavity wall

$$W = \frac{1}{2}\mu_0 \int_V |H|^2 \, dV = \frac{1}{2}\varepsilon_0 \int_V |E|^2 \, dV$$

Shunt impedance, R_a

$$R_a = \frac{U_a^2}{P_c}$$

RF Power Considerations

Dictated by:

- Accelerating Gradient, E_{acc}
- Beam Current, I_b
- Shunt Impedance, R_a
- Duty factor, DF
- RF Amplifier Efficiency, η_{rf}
- Cryogenic Carnot Efficiency (SC), η_{cryo}

Basic Cavity Comparison

Parameter	Unit	NC	SC
Frequency (MHz)	f	1500	1500
Accelerating Voltage (MV)	U_a	3	3
Temperature (K)	T	300	4.2
Surface Resistance (Ω)	R_s	0.0037	60×10^{-9}
Quality Factor	Q_o	20000	6×10^{9}
Shunt Impedance (MΩ)	R_a	40	12×10^{6}
Ra/Qo (Ω)		2000	2000
Cavity Power (W)	P_c	225000	3.6

$$\boxed{\frac{P_{nc}}{P_{sc}} \approx 63000}$$

AC Power Comparison (CW-No beam)

Parameter	**Unit**	**NC**	**SC**
Frequency (MHz)	f	1500	1500
Accelerating Voltage (MV)	U_a	3	3
Temperature (K)	T	300	4.2
Surface Resistance (Ω)	R_s	0.0037	60×10^{-9}
Quality Factor	Q_o	20000	6×10^{9}
Shunt Impedance (MΩ)	R_a	40	12×10^{6}
Ra/Qo (Ω)		2000	2000
Cavity Power (W)	P_c	225000	3.6
Cryogenic Static Load (W)			15
RF Amplifier Efficiency	η_{rf}	0.6	
Cryogenic Carnot Efficiency	η_{cryo}		0.003
AC Cavity Power (kW)		375	6.2

$$\boxed{\frac{P_{nc}}{P_{sc}} \approx 60}$$

AC Power Comparison (CW+Beam)

Parameter	Unit	NC	SC
Accelerating Voltage (MV)	U_a	3	3
Cavity Power (W)	P_c	225000	3.6
Cryogenic Static Load (W)			15
RF Amplifier Efficiency	η_{rf}	0.6	0.6
Cryogenic Carnot Efficiency	η_{cryo}		0.003
AC Cavity Power (kW)		375	6.2
Beam Current (mA)	I_b	20	20
Beam Power (kW)	P_b	60	60
AC Beam Power (kW)		100	100
Total AC Power (Cavity + Beam) (kW)	P_t	475	106.2

$$\boxed{\frac{P_{nc}}{P_{sc}} \approx 4.5}$$

AC Power Comparison (DF+Beam)

Parameter	Unit	NC	SC
Duty Factor (%)		1	1
Cavity Power (W)	P_c	225000	3.6
Cryogenic Static Load (W)			15
RF Amplifier Efficiency	η_{rf}	0.6	0.6
Cryogenic Carnot Efficiency	η_{cryo}		0.003
AC Cavity Power (kW)		375	6.2
Pulsed Cavity Power (kW)		3.75	5.0
Beam Current (mA)	I_b	20	20
Beam Power (kW)	P_b	60	60
AC Beam Power (kW)		100	100
Pulsed Beam Power (kW)		1	1
Total Pulsed AC Power (Cavity + Beam) (kW)	P_t	4.75	6.0

$$\frac{P_{nc}}{P_{sc}} \approx 0.8$$

Ref: Holger Podlech (IAP Frankfurt), CERN Accelerator School: Course on High Power Hadron Machines; 24 May - 2 Jun 2011, Bilbao, Spain

RF Technology Preference

Normal Conducting	Superconducting
• Low Energy	• High Energy
• High Beam Power	• Low Beam Power
• Low Duty Factor	• High Duty Factor

Gradient Limitations

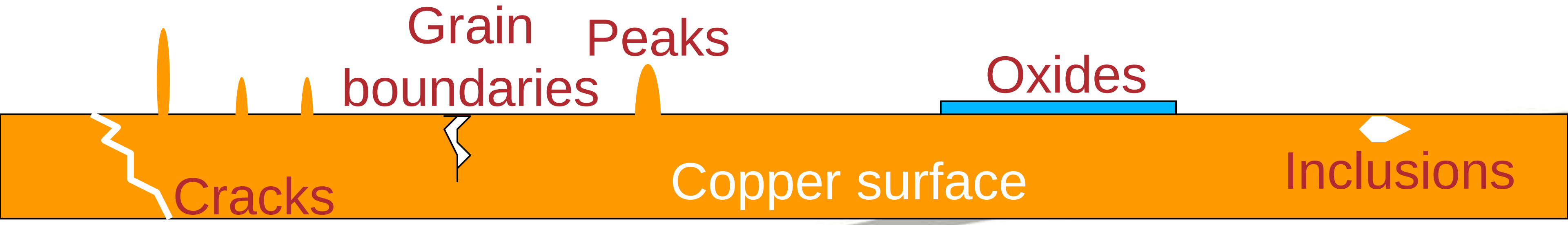
Breakdown

- The maximum achievable gradient in RF structures is limited by the breakdown phenomenon
- Physics not yet fully understood quantitatively
- Developing an understanding will impact on
  - The design
  - Material choice
  - Construction of rf structures

⇨Therefore, understanding breakdowns has great importance to reaching higher gradients with an acceptable breakdown probability

Surface Impurities

- The surface of an accelerating structure will have a number of imperfections at the surface caused by:-
  - Grain boundaries
  - Impurities
  - Inclusions
  - Scratches
  - Surface localised peaks
- As the surface is an equipotential the electric fields at these small imperfections can be greatly enhanced causing field emission



(suggested by Wuensch and colleagues)

Field Emission

- Surface impurities are more problematic for SC cavities, due to low intrinsic losses
- Cavity power increases faster than the stored energy, due to non-ohmic losses:
  - Acceleration of field-emitted electrons
  - Electrons hitting cavity walls – generates X-rays
  - Causes localised heating
    - ➪ Leading to thermal breakdown, when $T>T_c$
    - ➪ Leading to a quench
- Cavity Q-factor drops at high voltages
- ➢ SC cavities require careful preparation:
  - ▪ Chemical polishing, HP water rinsing and cleanroom assembly
- Maximum surface magnetic field limitation for Nb of ~ 200mT (geometry dependent)

Field Emission

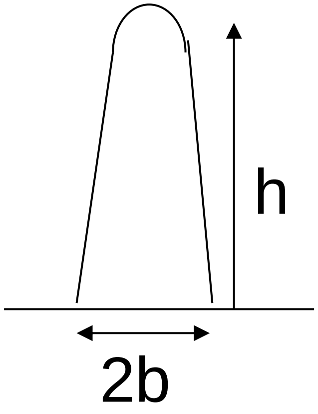
Fowler Nordheim Law (RF fields):

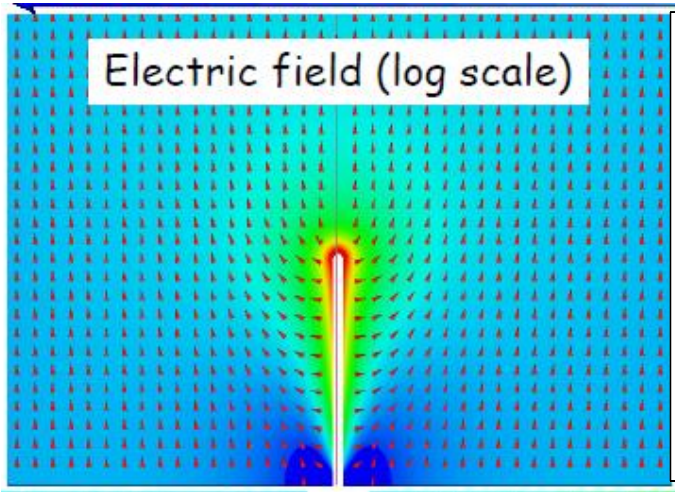
$$\bar{I} = \frac{5.79\times10^{-12}\exp(9.35\varphi_0^{-0.5})A_e(\beta E_0)^{2.5}}{\varphi_0^{1.75}}\exp\left(\frac{-6.53x10^{9}\varphi_0^{1.5}}{\beta E_0}\right)$$

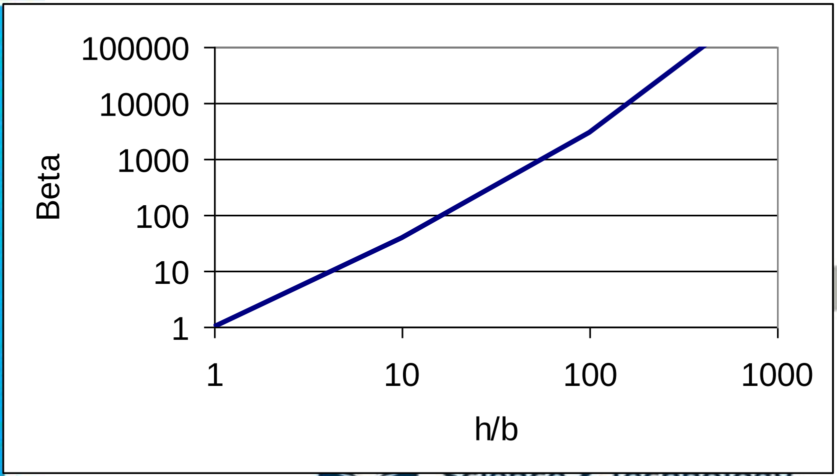
- High field enhancements (β) can field emission
- Low work function (ϕ_0) in small areas can cause field emission

- As the surface is an equipotential the electric fields at these small imperfections can be greatly enhanced
- Typically β is between 50 - 100
- In some cases the field can be increase by a factor of several hundred

$$E_{local}=\beta E_0$$







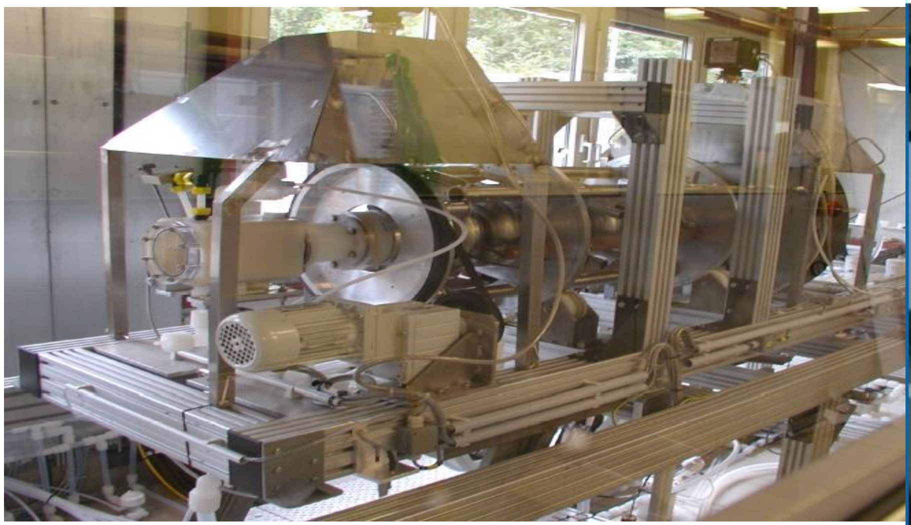
Buffered Chemical Polish

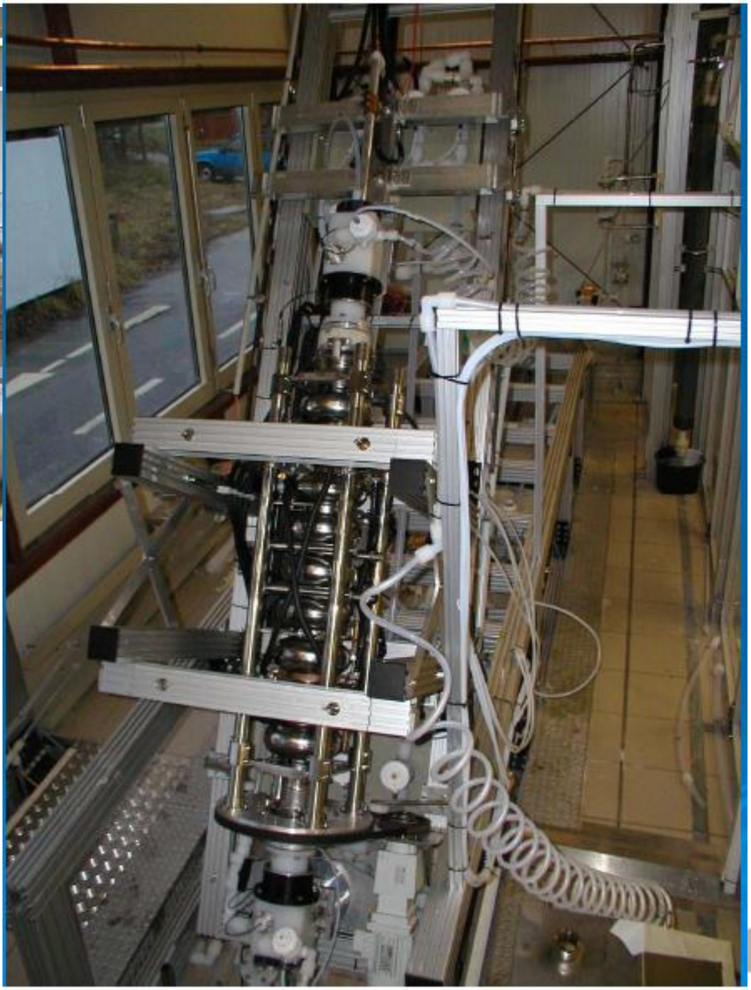
- In order to remove any defects or damage to the surface, an acid etch is applied to the cavities

➪ Buffer Chemical Polish (BCP) removes 100-150µm

- Acid mixture
    - Hydrofluoric acid; HF (49%)
    - Nitric Acid; HNO_3 (65%)
    - Phosphoric Acid; H_3PO_4 (85%)
    - In a 1:1:1 mixture
- Risk of hydrogen contamination
    - Correct mixture should be used
    - Temperature of acid should be kept below <18 °C, to control the exothermic reaction
    - Vacuum processing required
- Cavity is the high pressure rinsed (HPR) with ultrapure water

Electropolish (EP)

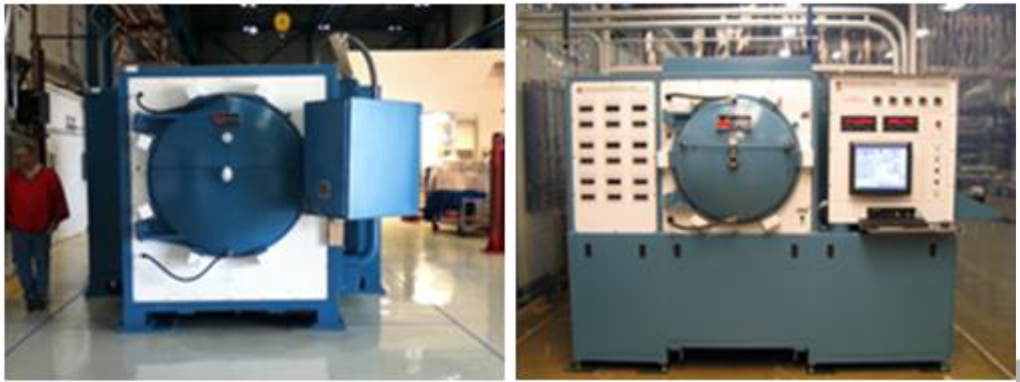




- Electropolishing achieves a smoother finish than BCP and typically higher gradients
- The cavity is an anode and an aluminium cathode is immersed in an electrolyte
- Again hydrogen is produced so vacuum processing and HPR are required

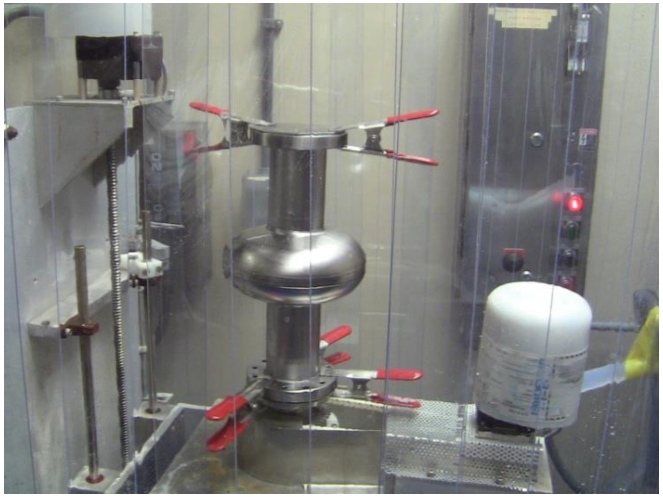
Vacuum Processing

- High temperature vacuum baking of the cavity is another method of reducing surface contamination
  - Reduction of hydrogen from chemical etching
- Numerous recipes
  - 600ºC for 8 hours
  - 800ºC for 2 hours
  - Even 1000ºC for ~2 hours

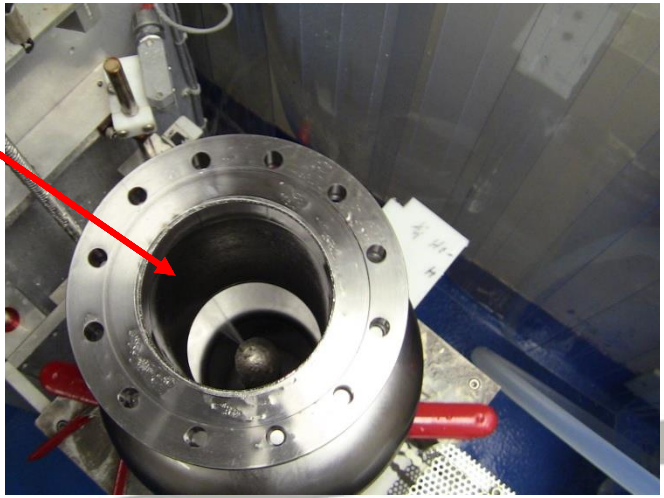


MP9 and IB4 Vacuum Furnaces at FermiLab

High Pressure Rinse

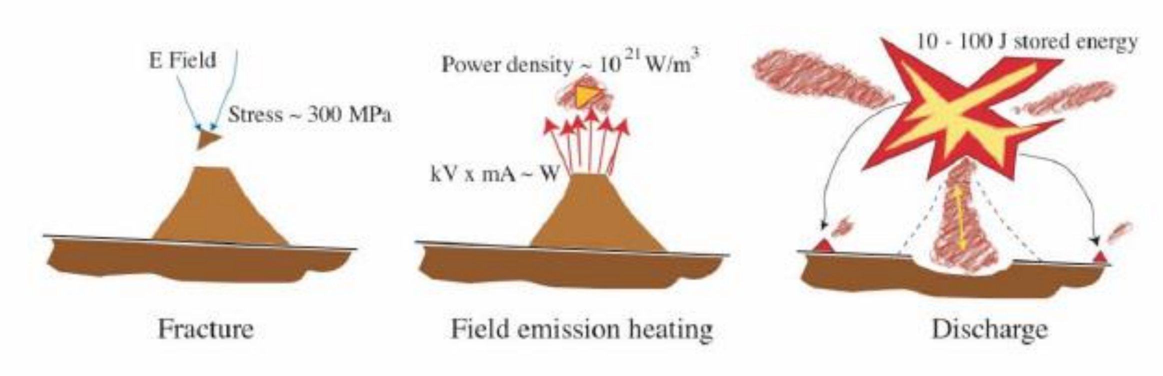


- After etching it is necessary to perform a high pressure rinse (HPR) the cavity using ultra pure water, in a cleanroom
- The rinsing facility uses small nozzles to direct the water
- Performs an aggressive removal of particulates
  - High pressure (~100 bar) rinsing is often performed in a clean room.
- Care must be taken not to use metal parts as UPW is highly corrosive.



RF Conditioning

- As after manufacture and processing of a cavity there still remains a number of nucleation sites for breakdown it is necessary to condition the cavity
- Typically the RF power and RF pulse width are gradually increased over a period of hours/days
- The conditioning consists of a number of semi-controlled RF breakdowns as the RF power is increased
- A plasma discharge is generated in the cavity causing vaporisation of the nucleation site just above the breakdown threshold causing a minimum amount of damage

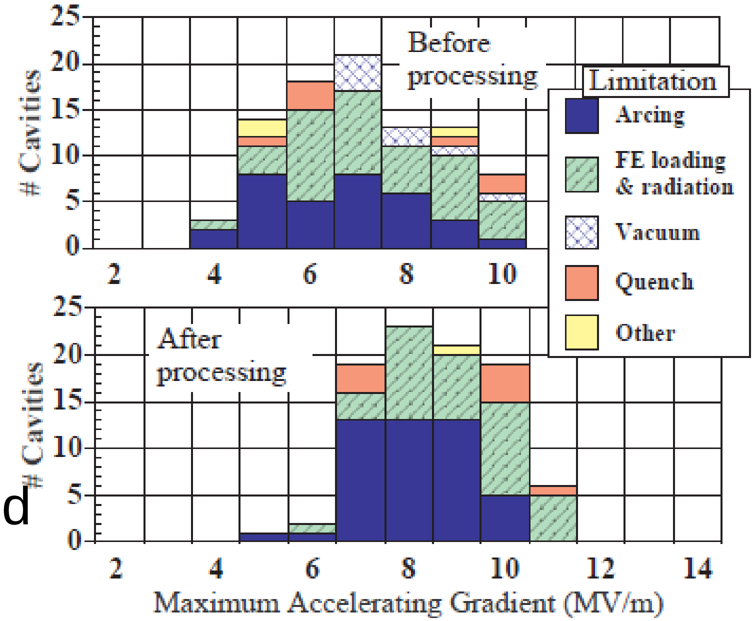


Helium Processing

- Additional RF processing can be performed

⇨ Helium processing

- In the presence of a partial pressure of helium (1x10^{-5} torr), the cavity can be RF conditioned
- Reduction in field emission
- Electric field performance gains of 10–20% have been achieved
- The mechanism is not yet clearly understood
- It is believed:-
    - ⇨ The FE current locally ionizes the helium gas
    - ⇨ Forming a local plasma
    - ⇨ This heats and melts the emission source
    - ⇨ Provides microscopically directed helium ion bombardment of the source, or enhances the local field to the point of drawing out current densities sufficient to explode the emitter



Helium processing performed at JLab on the CEBAF 1.5GHz SRF cavities

Thermal Limitations

- For CW cavities, the cavity temperature reaches steady state when the water cooling removes as much power as is deposited in the RF structure
- Temperature rises can cause surface deformation, surface cracking, outgassing or even melting
- Pulsing the RF can enable much higher gradients as the average power is reduced

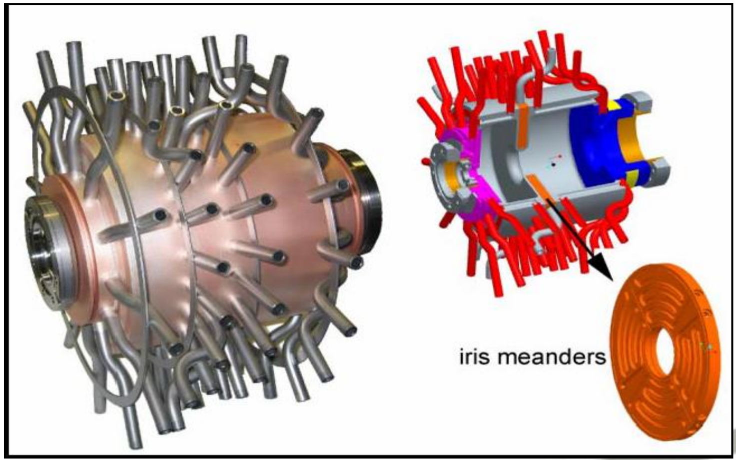
Thermal Limitations

Normal conducting:

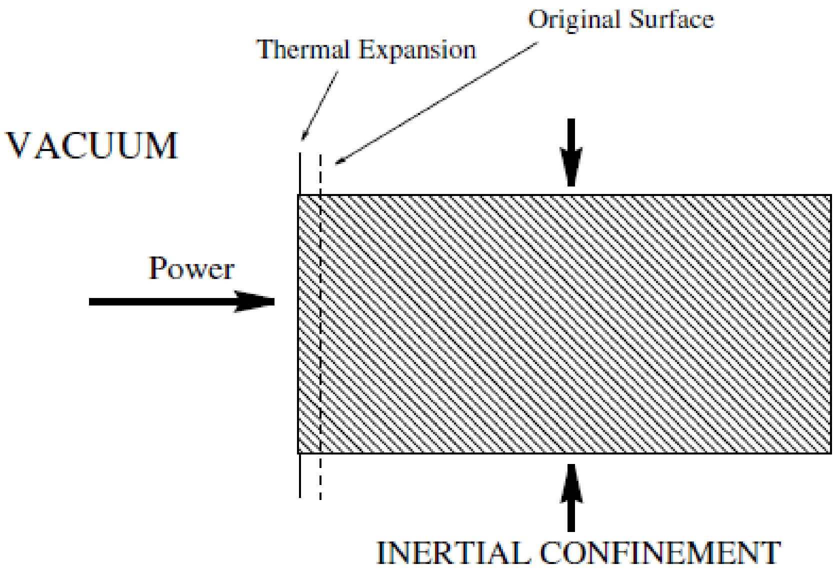
- Thermal dissipation at high duty factors:
  - – Becomes difficult to remove heat above a limit of ~ 100kW/m (material conductivity dependent).
  - – Not an issue for SC, as thermal losses are much lower

1.3GHz, 1kHz rep-rate photo-gun (BESSY)

⇨ Pc ~ 75 kW

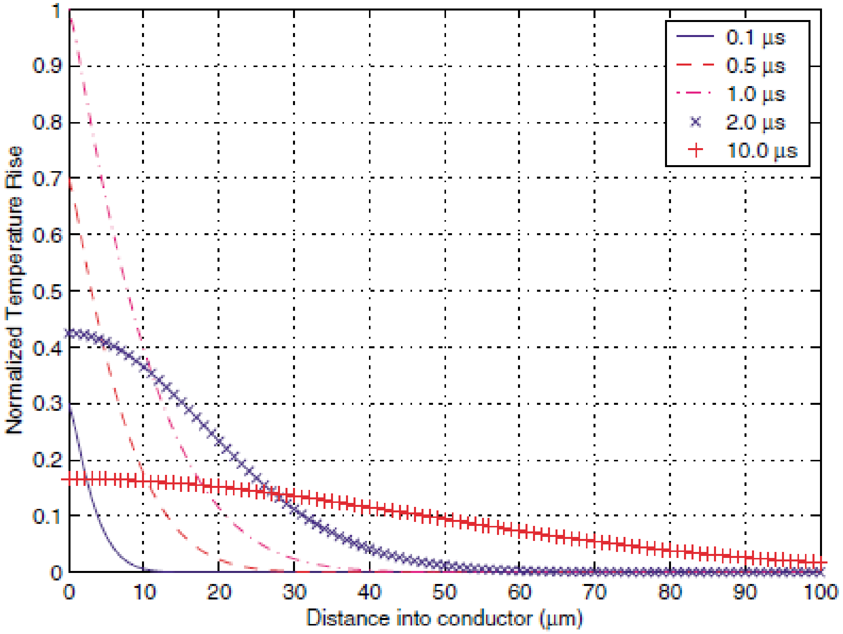


Pulsed Heating



$$T_s = \frac{P_d\sqrt{\tau}}{2\sqrt{\pi \rho k c_\epsilon}}, \quad D_d = \sqrt{\frac{k\tau}{\rho c_\epsilon}}, \quad T_s = \frac{P_d D_d}{2\sqrt{\pi}k}, \qquad (1)$$

where $\rho = 8.95 \cdot 10^3 \frac{kg}{m^3}$, $k = 391 \frac{W}{m \cdot K}$ and $c_\epsilon = 385 \frac{J}{kg \cdot K}$ are the density, the heat conductivity and the specific heat for OFC copper.

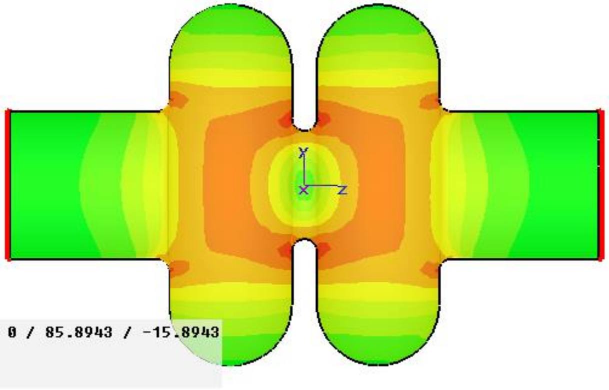


- Pulsed RF however has problems due to heat diffusion effects
- Over short timescales (<10ms) the heat doesn't diffuse far enough into the material to reach the water cooling
- This means that all the heat is deposited in a small volume with no cooling
- Cyclic heating can lead to surface damage

Cavity Design

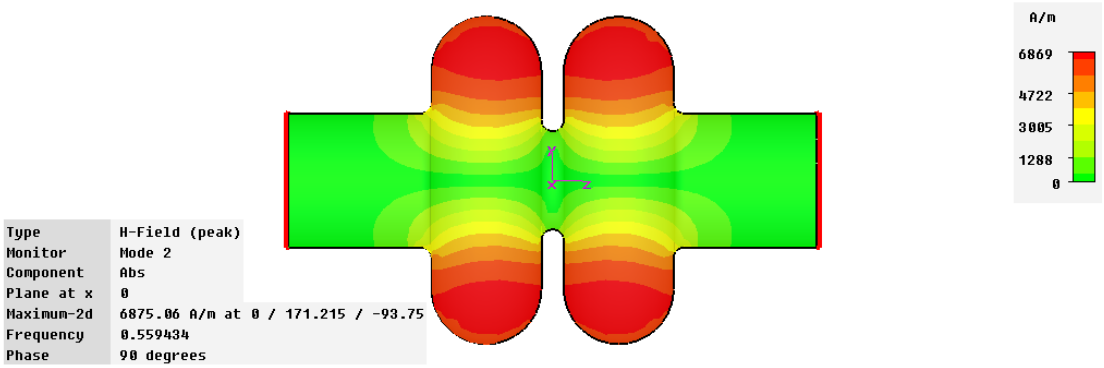
- Further gains in attainable accelerating gradient have been achieved through alteration of cavity geometry
- Minimize the ratio of peak surface field to accelerating gradient
- Maximising the accelerating gradient with respect to the maximum surface electric field and magnetic field

$$E_{acc} = \frac{|V|}{d} \qquad \frac{E_{acc}}{E_{\max}} \qquad \frac{E_{acc}}{B_{\max}}$$



```
0 / 85.8943 / -15.8943
```

Electric Field Magnitude



```
Type          H-Field (peak)
Monitor       Mode 2
Component     Abs
Plane at x    0
Maximum-2d    6875.06 A/m at 0 / 171.215 / -93.75
Frequency     0.559434
Phase         90 degrees
```

Magnetic Field Magnitude

Cavity Design

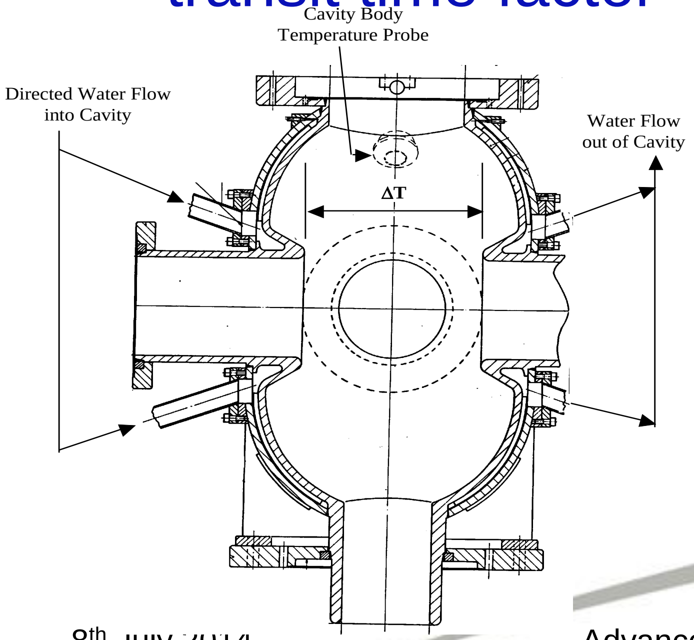
- Accelerating voltage for a cavity:

$$V = \Re\left\{\int_{-L/2}^{+L/2} E_z(z,t)\,e^{i\omega z/c}\,dz\right\} = E_{z0}LT\cos(\omega t)$$

E_{zo}= Peak electric field
T= Transit time factor

- Decreasing the accelerating gap, whilst maintaining the same voltage between the gap,

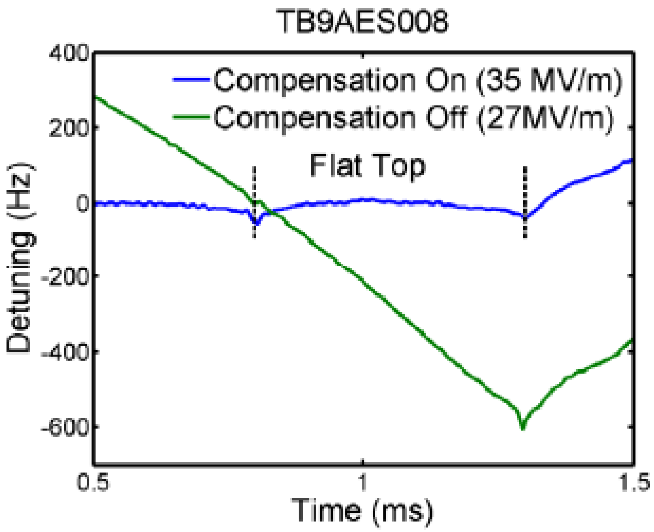
⇨ Increases the effective accelerating voltage due to the transit time factor



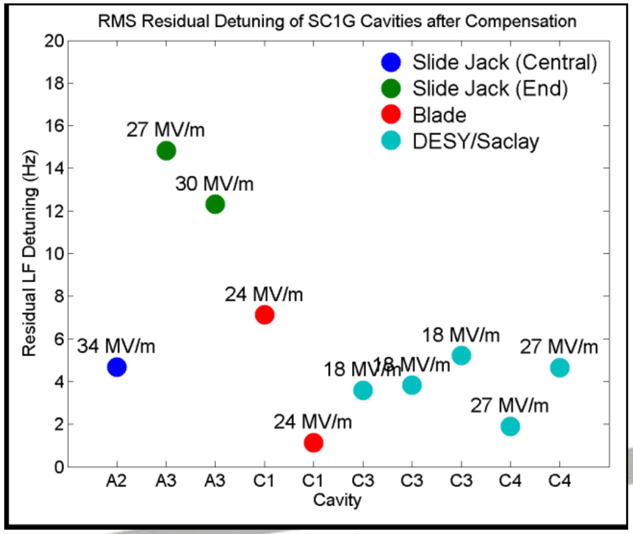
- However surface electric fields are increased
- To minimise effects the nose cone is only decreased

Lorentz Force Detuning

- EM fields induce a pressure resulting in a cavity field level deformation and frequency shift.
- Mainly problematic for high-field, pulsed, thin-walled SC cavities
- Fast piezo tuners and feed-forward compensation techniques employed



W Schappert (FNAL)



Current Challenges and R&D

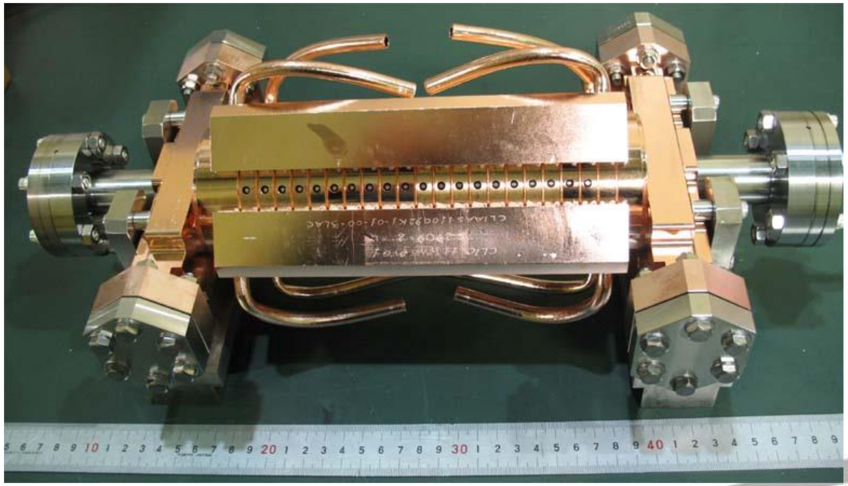
CLIC Accelerating Structure Development

- CLIC is a 3 TeV concept facility
- Accelerating gradient of x-band structures of ~100 MV/m is required
- Main linac cavities are required to maintain low beam emittance and meet the luminosity requirements

⇨ Must be built with a few micron tolerances

⇨ Aligned along 10’s of meters with roughly 10 micron tolerances

⇨ This means that accelerating structures must be equipped with higher order mode in order to suppress



Courtesy: Walter Wuensch (CERN)

Structure Design

- Design optimised for:-
  - Surface electric and magnetic field (pulsed surface heating)
  - Global power flow

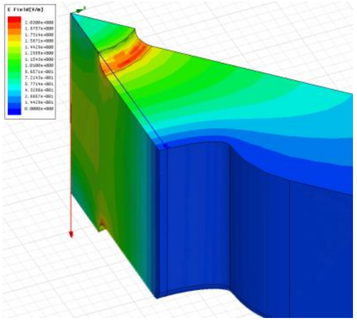
$$\frac{P}{\lambda C} = \mathrm{const}$$

  - Local complex power flow

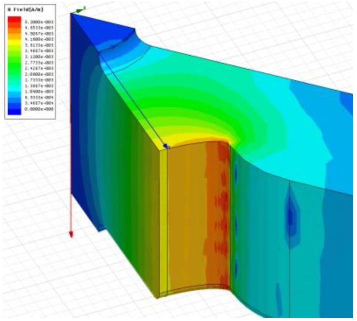
$$S_c = \mathrm{Re}(\mathbf{S}) + \frac{1}{6}\mathrm{Im}(\mathbf{S})$$

  -

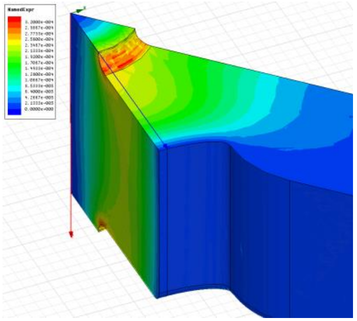
E_s/E_a



H_s/E_a



S_c/E_a^2



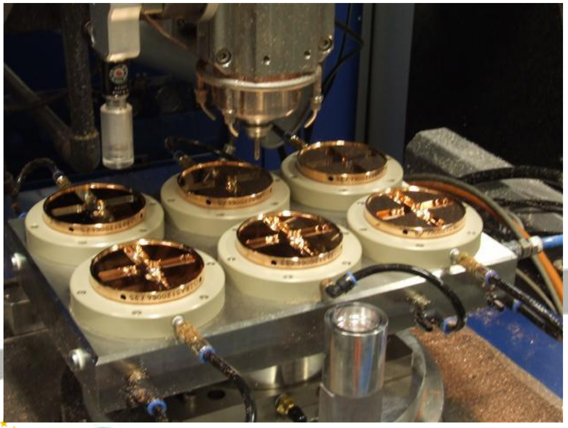
A. Grudiev, S. Calatroni, W. Wuensch (CERN). 2009. 9 pp.
Published in Phys.Rev.ST Accel.Beams 12 (2009) 102001

Micron Precision Turning & Milling

- Accelerating structure tolerances drive transverse wakefields and off-axis RF induced kicks
  - Leads to emittance growth
  - ⇨ Micron tolerances required
- Multi-bunch trains require HOM wakefield suppression
  - ⇨ Cell design requires milled features

⇨ High-speed diamond machining
  - ⇨ Beneficial for high-gradient performance
    - Minimises induced surface stresses

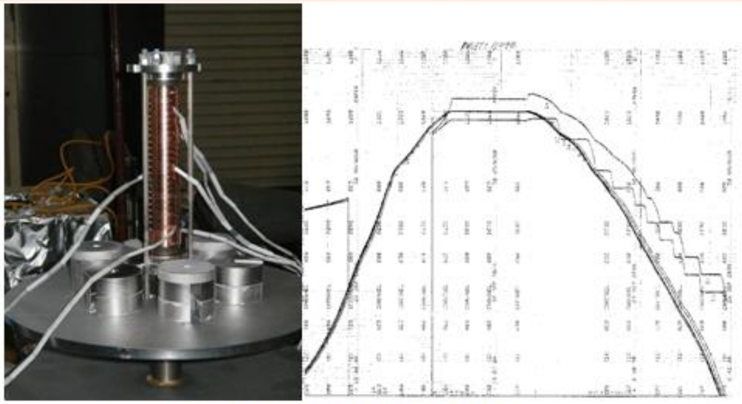
Development done “in industry”



Cavity Manufacture

Stacking disks

Diffusion Bonding of T18_vg2.4_DISC



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

Holding for 1 hour at 1020° C

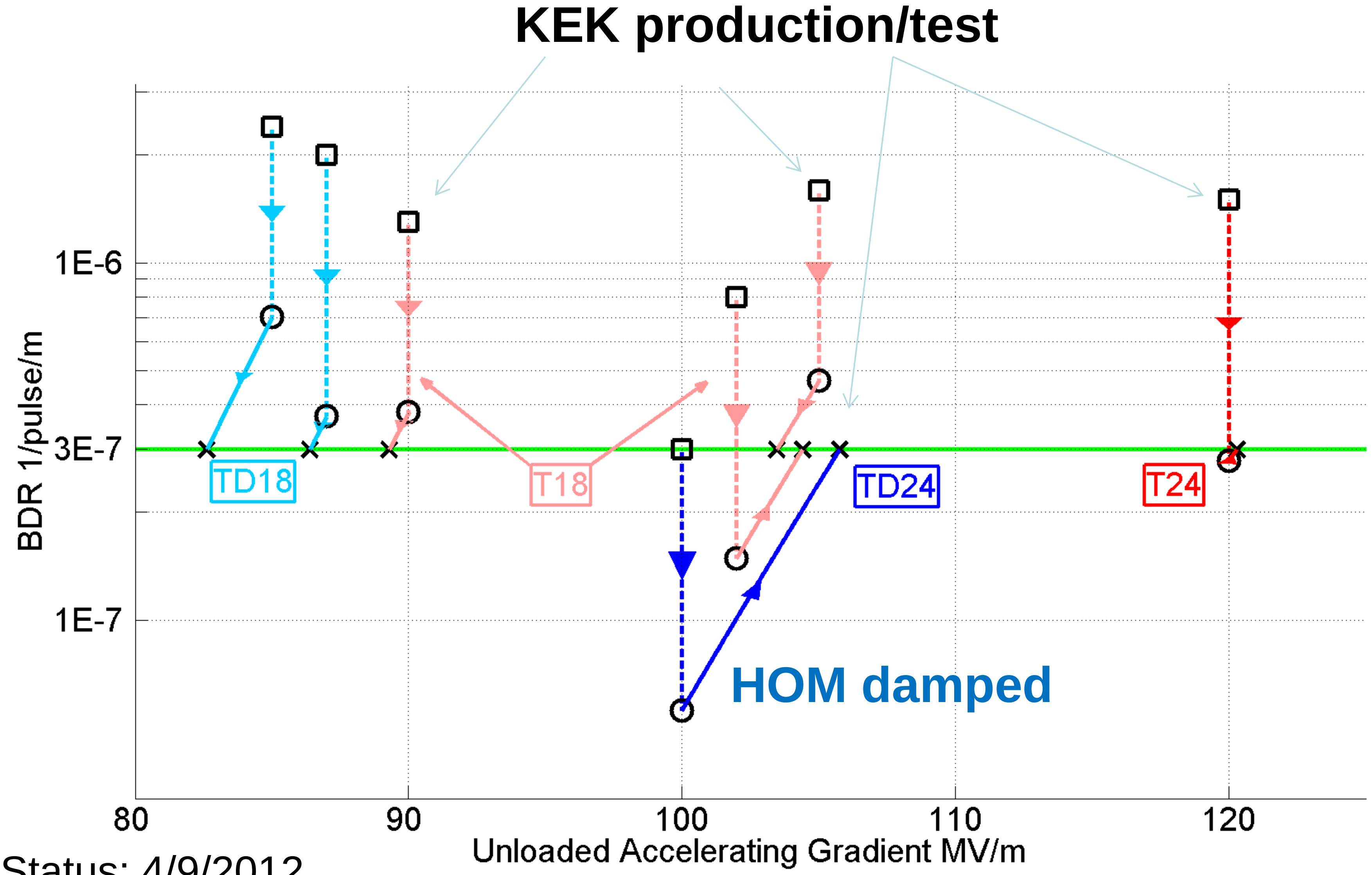
Vacuum Baking of T18_vg2.4_DISC

650° C

10 days

- Diffusion bonding
- Vacuum backing
  - – Temperature treatment for high-gradient developed by NLC/JLC

Test Performance



Status: 4/9/2012

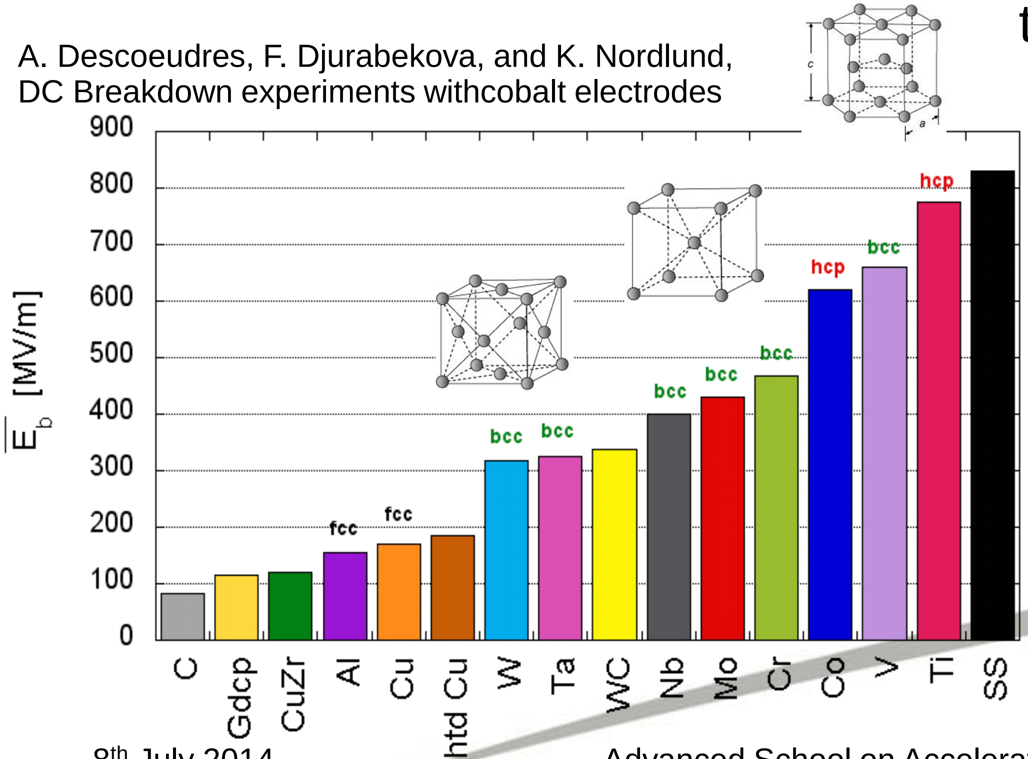
DC Breakdown Studies at CLIC

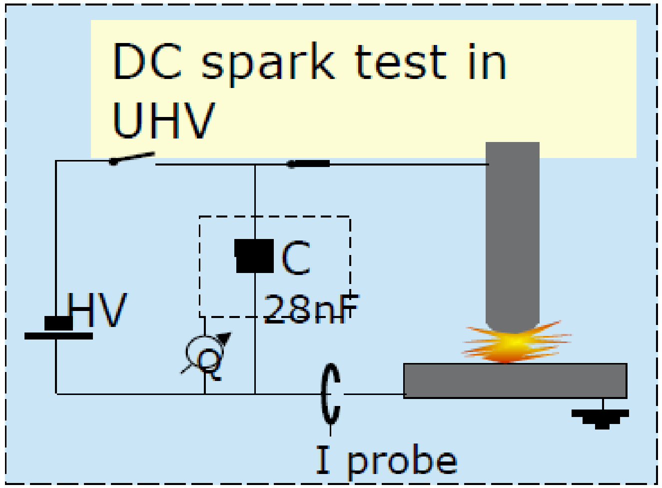
Motivation for DC experiment:

- Understanding breakdown mechanism in simpler system than RF requires:
  - Many tests
  - Reproducibility checks
  - Analysis of various materials
  - Analysis of parameters

- Results show the saturated field of various materials
- The dislocation motion is strongly bound to the atomic structure of metals
- ➢ In FCC (face-centered cubic) the dislocations are the most mobile
- ➢ HCP (hexagonal close-packed) are the hardest for dislocation mobility

A. Descoeudres, F. Djurabekova, and K. Nordlund, DC Breakdown experiments withcobalt electrodes



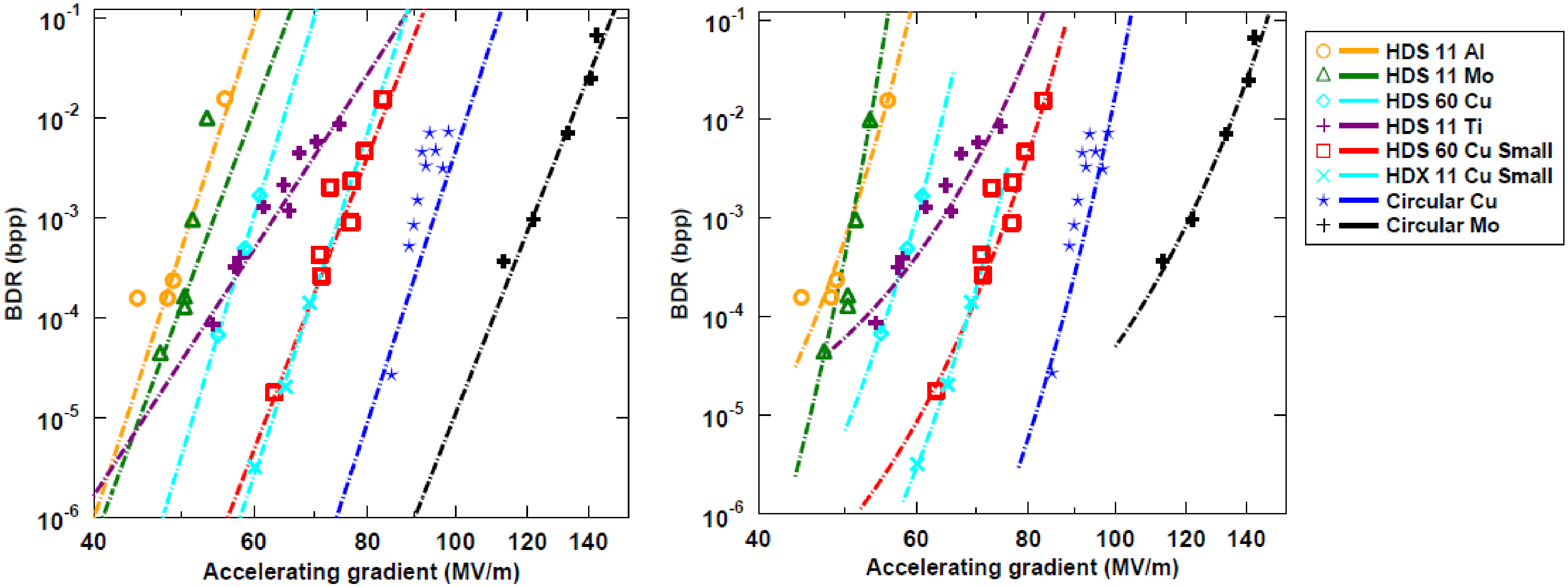


Courtesy: M. Taborelli

Dislocation-based model for electric field dependence

- Analysis of experimental data
- The result is:

$$BDR = Ae^{\varepsilon_0 E^2 \Delta V / kT}$$



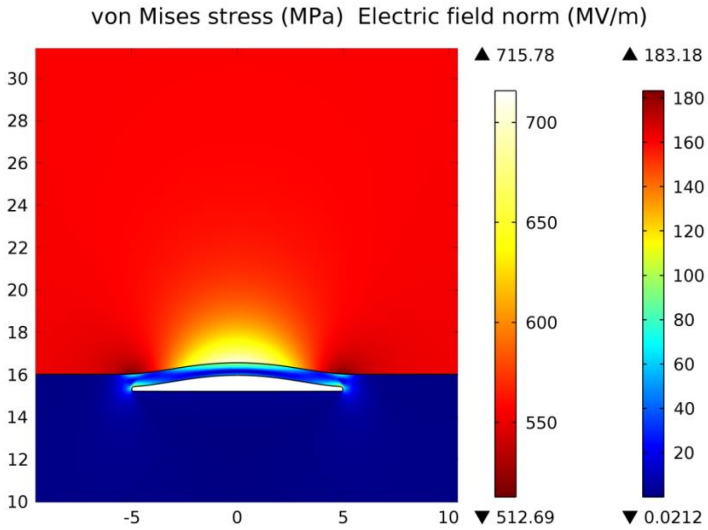
Power law fit

Stress model fit

[W. Wuensch, public presentation at the CTF3, available online at http://indico.cern.ch/conferenceDisplay.py?confId=8831.] with the model.]

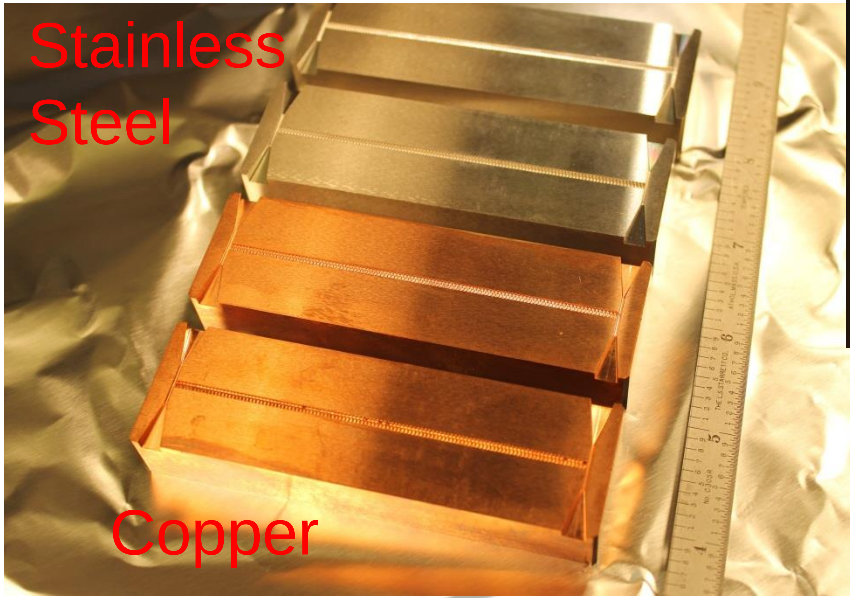
Material Deformation

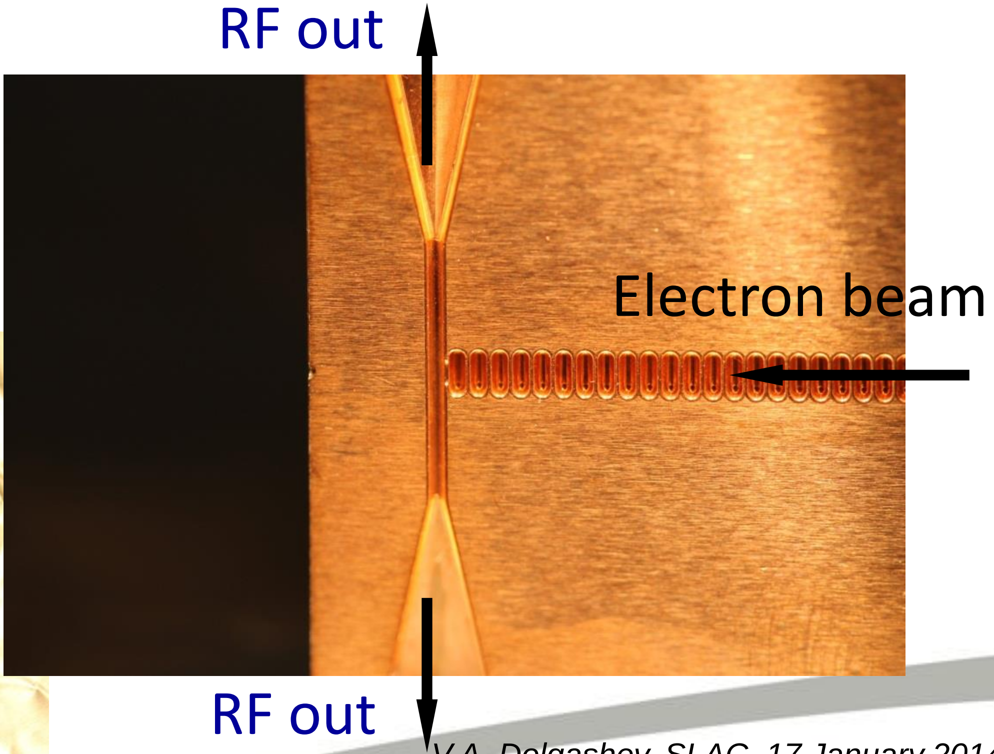
- Prediction of material deformation in high electric field regions
- Voids can be formed in a region of fragile impurities at fields > 400 MV/m
- Material is plastic only in the vicinity of the defect
- Field enhancement factor ~2.4



RF Breakdown Studies at SLAC

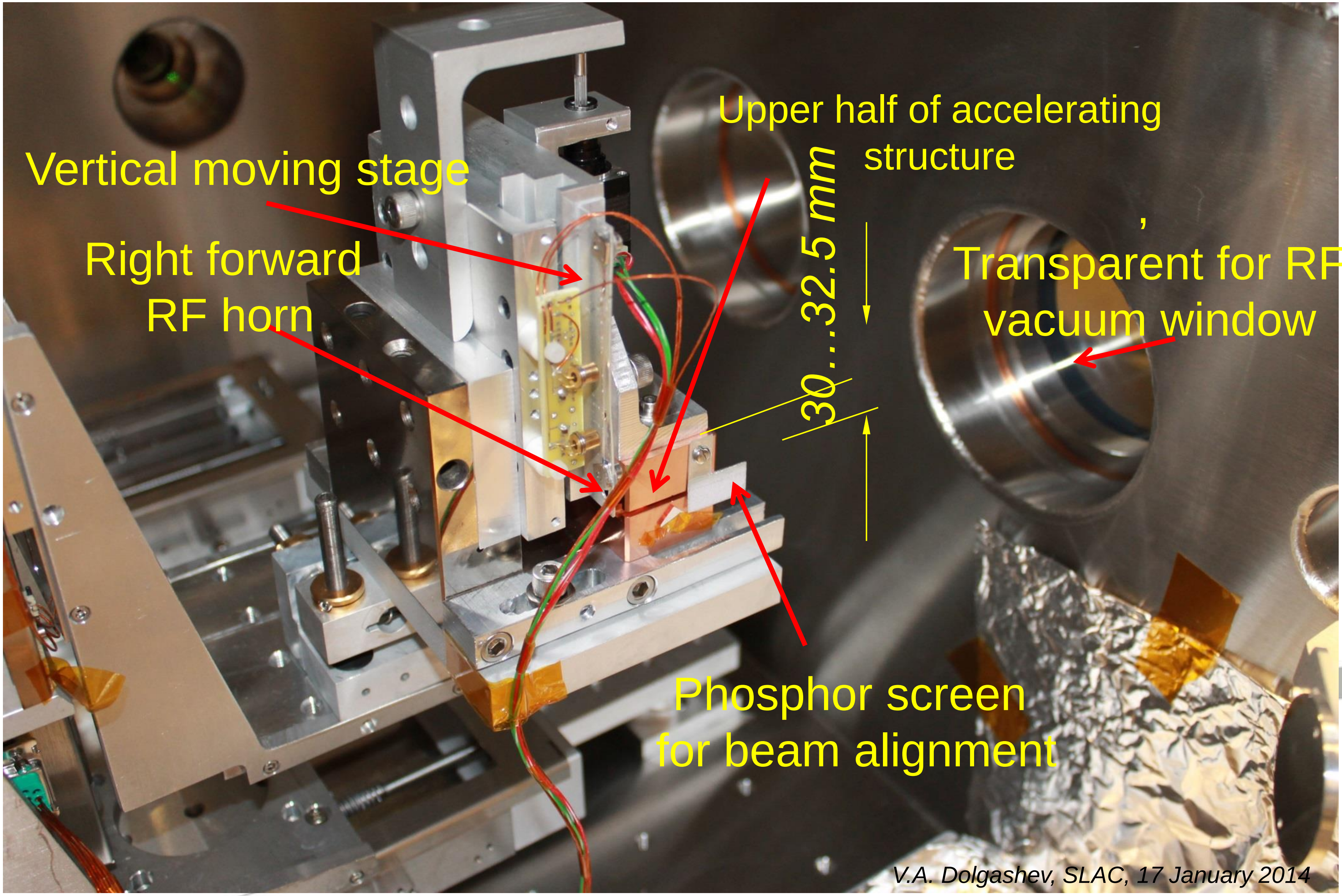
- Beam driven tests on FACET (Facility for Advanced Accelerator Experimental Tests) to determine statistical properties for RF breakdown properties in 100 GHz structures
  - Copper
  - Stainless steel
- Examining effect of
  - Geometry
  - Accelerating gradient
  - Pulse length
- Tests on going



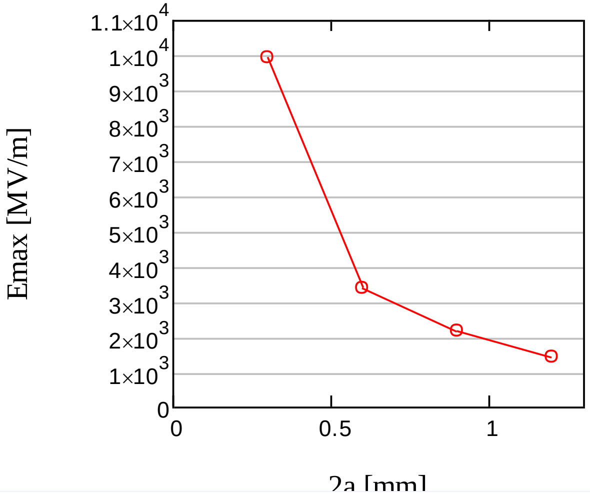


V.A. Dolgashev, SLAC, 17 January 2014

FACET - Copper Structure in Vacuum Chamber

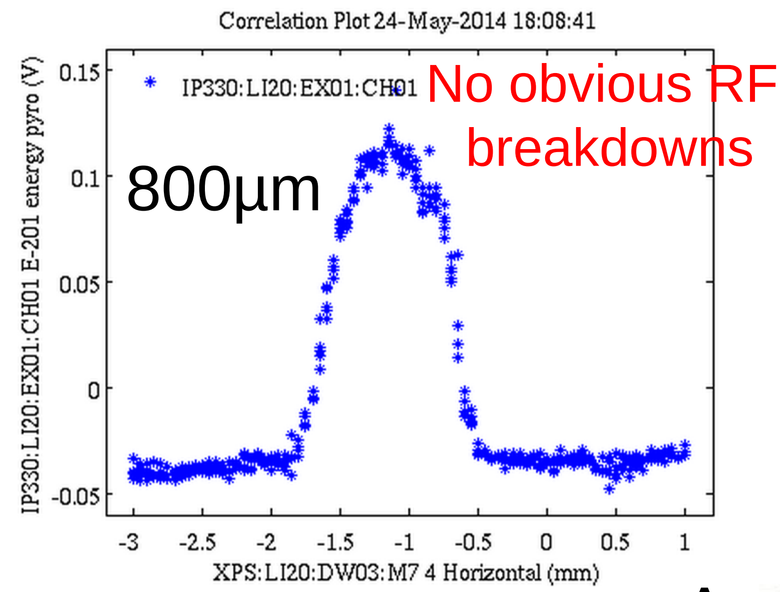


Performance Tests



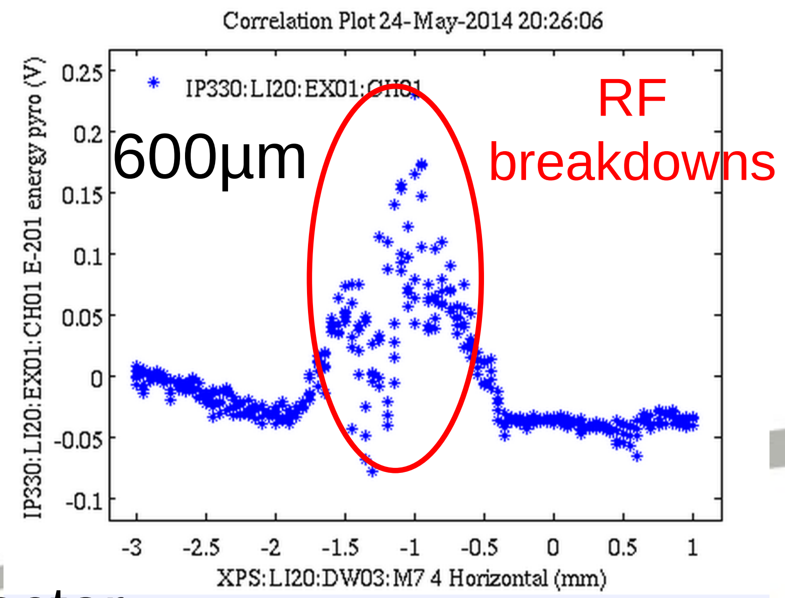
Accelerating gradient for structure with changing beam gap, excited by 2.7 nC bunch

Stainless steel performance



800µm

No obvious RF breakdowns



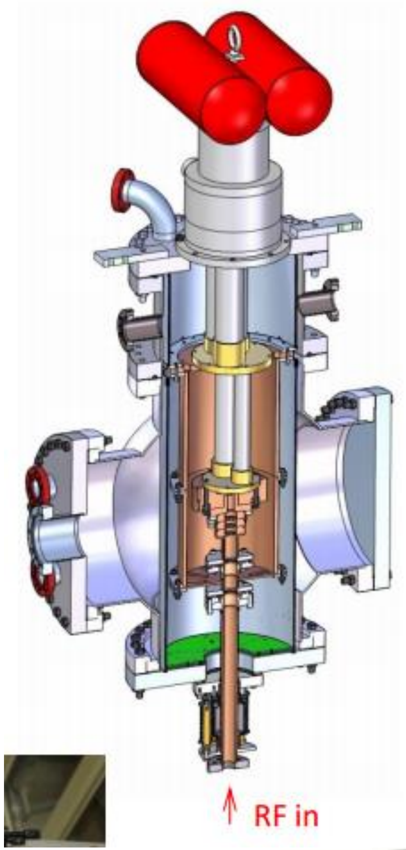
600µm

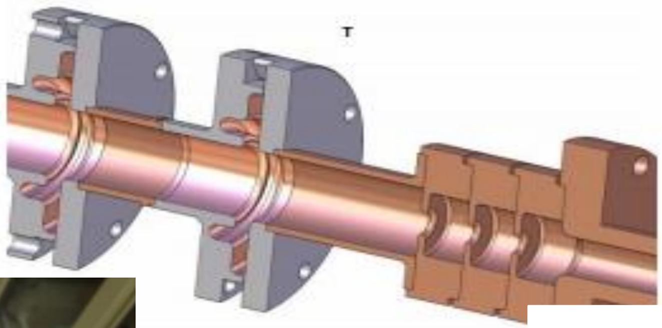
RF breakdowns

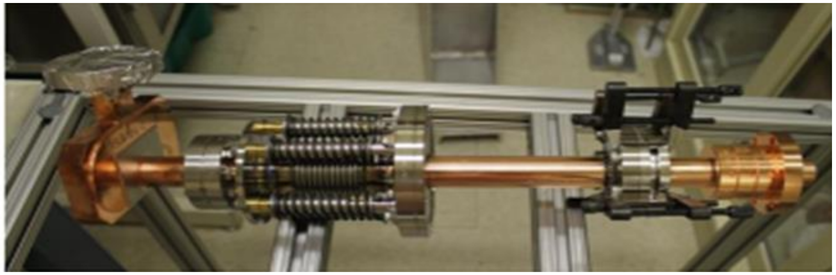
Arc-detector

SLAC Cryo-cooled Structure

- Conductivity increases (by a factor of 17.6 at 25 K) enough to reduce cyclic stresses
- Yield strength of copper increases

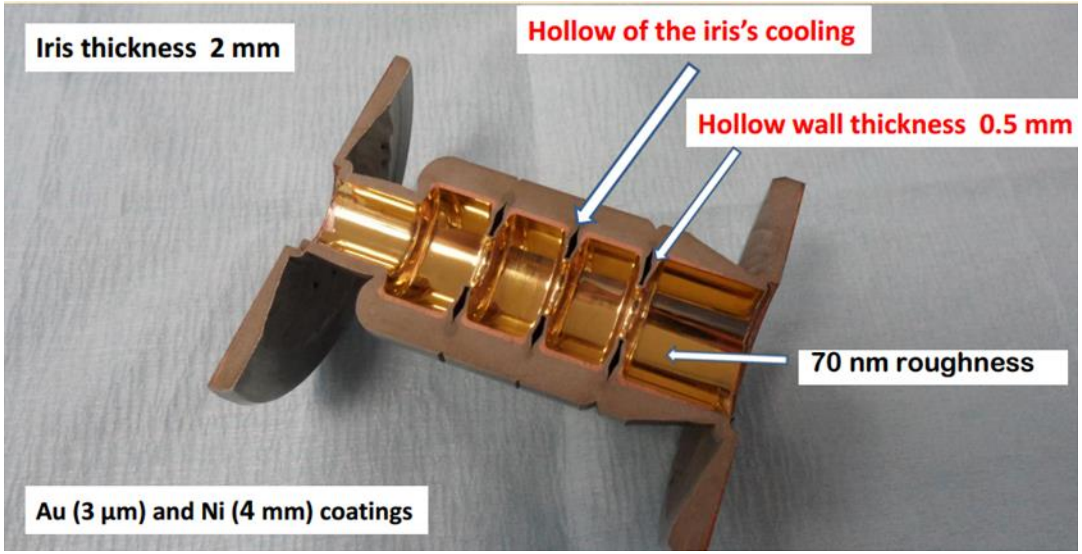


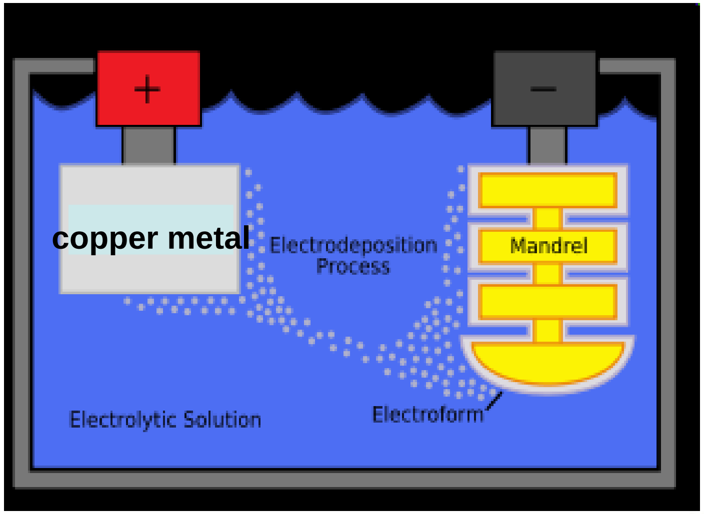




Dolgashev *et al*., IPAC 12

NORCIA Electroforming

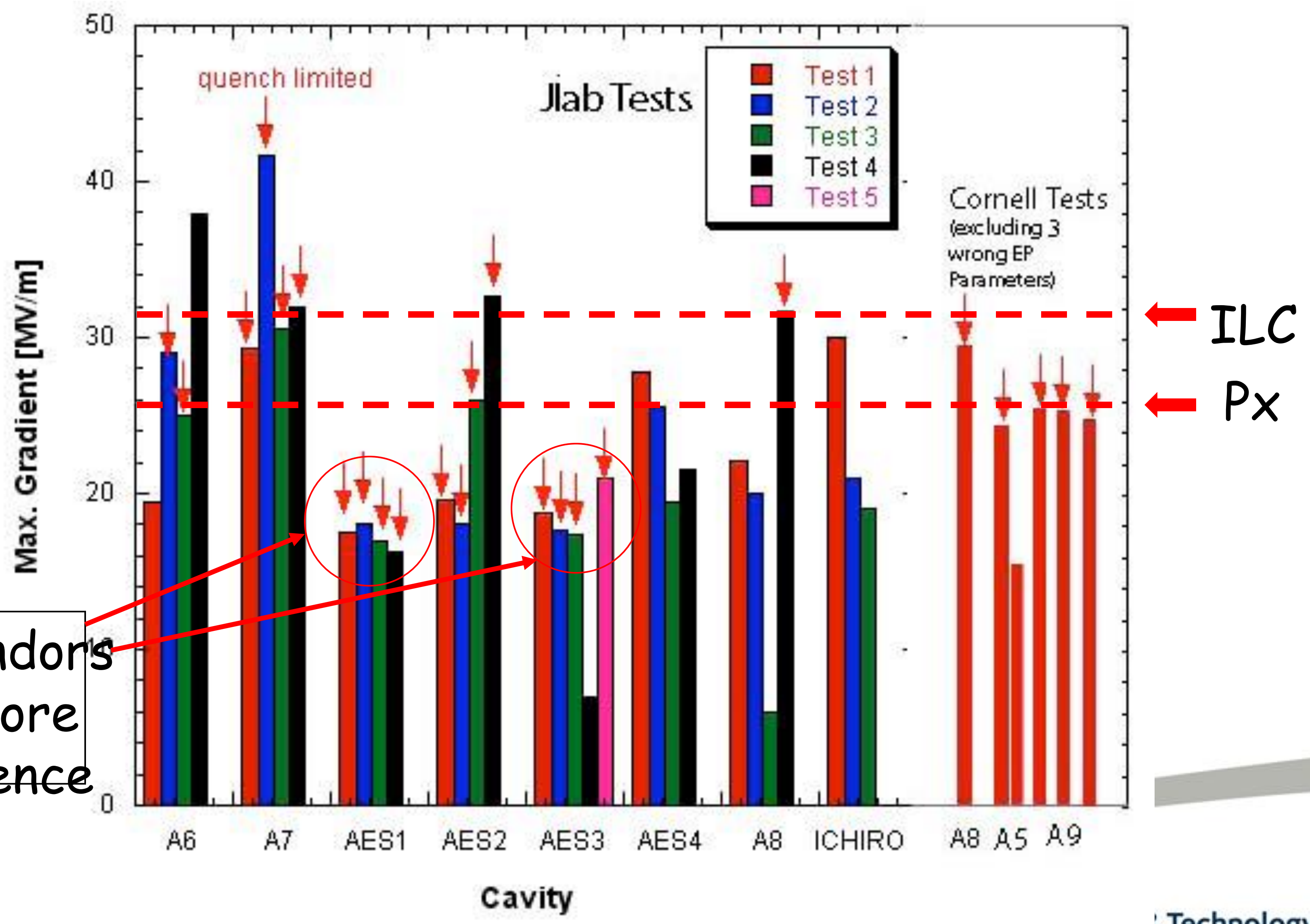




- NORCIA Group
  - INFN-LNF
  - SLAC
  - KEK
- Single and multi-layer electroformed cavities
- Alternative to brazing
- Built in iris cooling channels

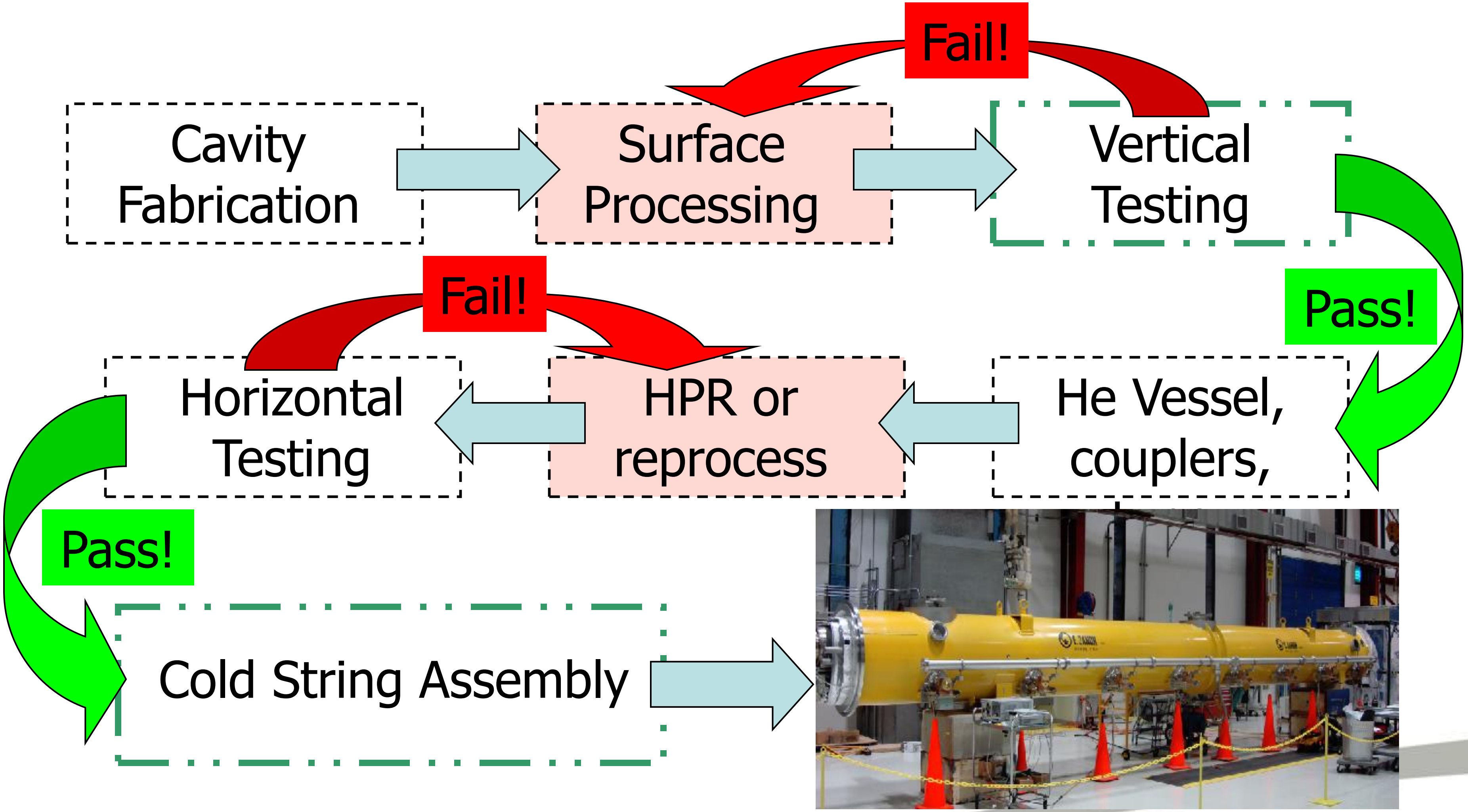
Bruno Spataro
INFN

Early 9-cell Cavity Test Results in US



US Vendors need more experience

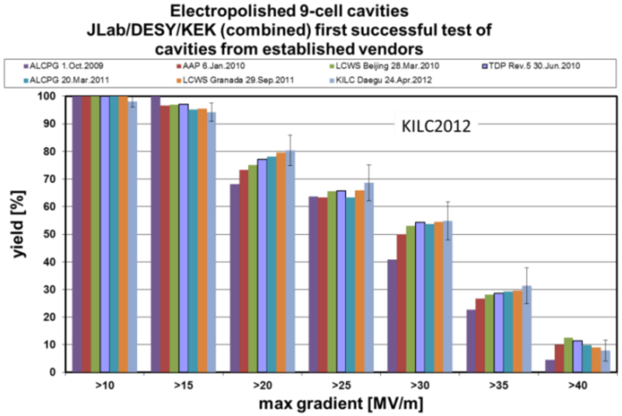
SRF Cavity/CM Process and Testing

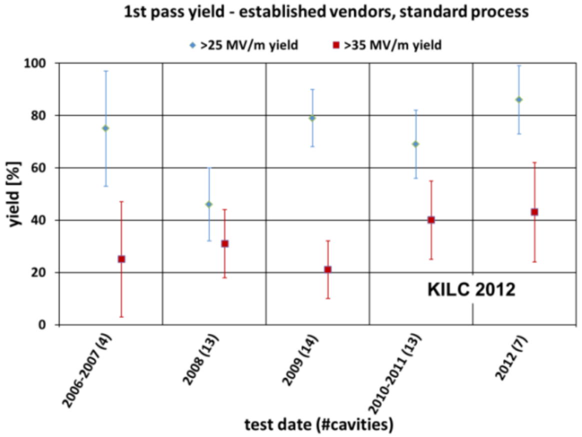


- Development of a standard process
  - Labs and industry

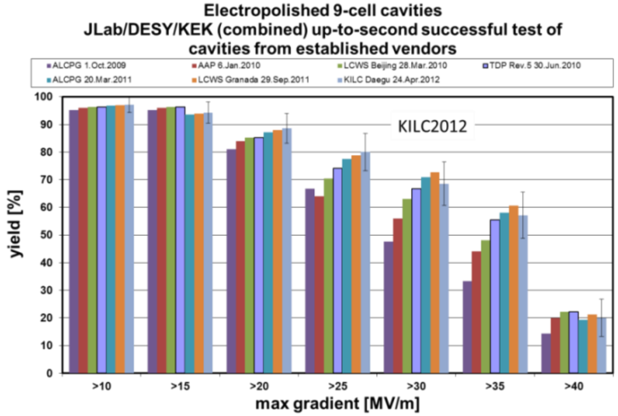
ILC Cavity Performance Benchmark

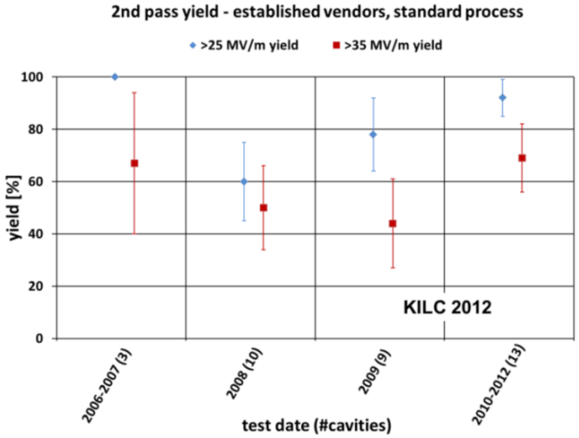
1st pass


Electropolished 9-cell cavities
JLab/DESY/KEK (combined) first successful test of
cavities from established vendors


1st pass yield - established vendors, standard process

2nd pass

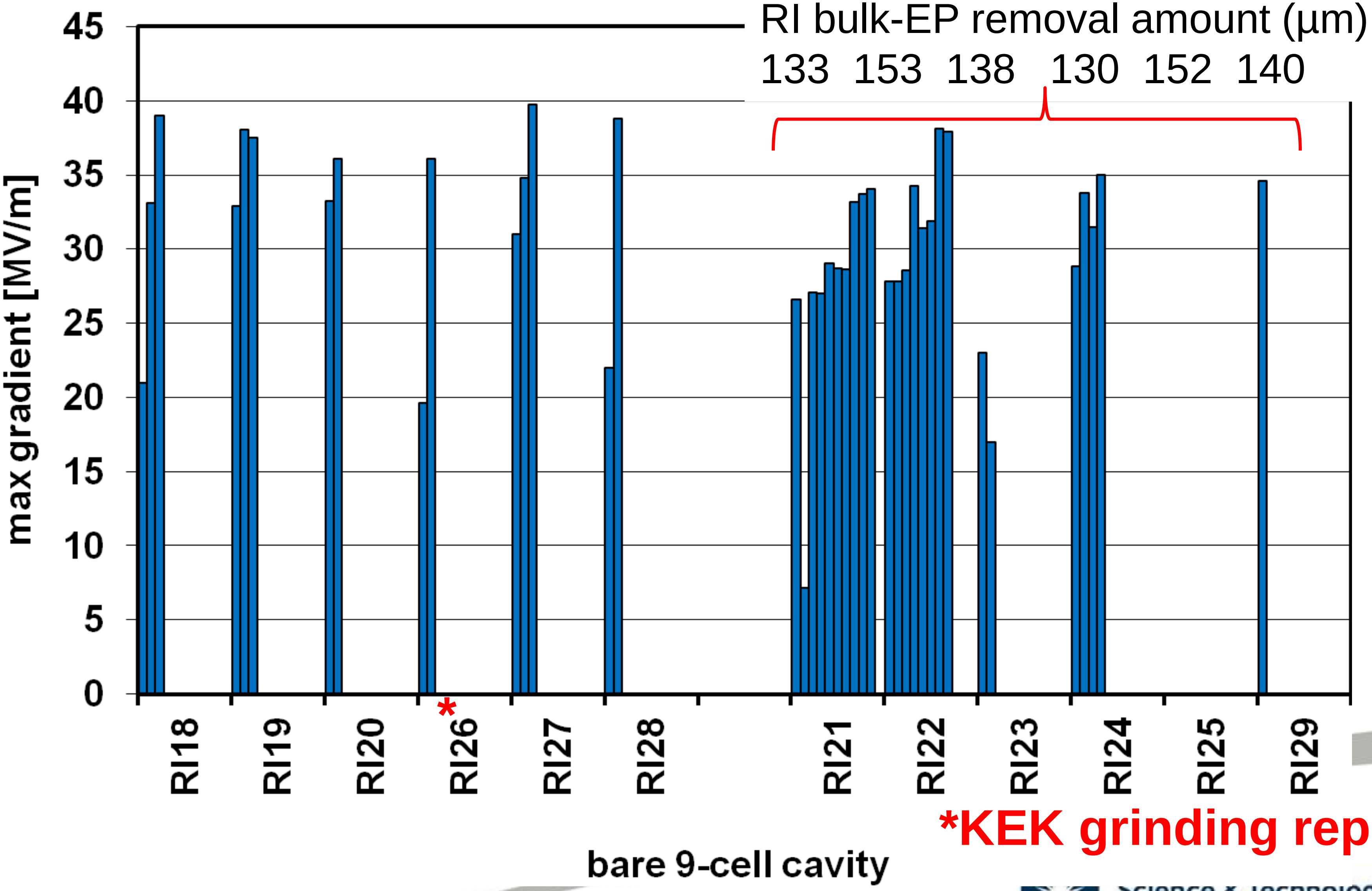

Electropolished 9-cell cavities
JLab/DESY/KEK (combined) up-to-second successful test of
cavities from established vendors


2nd pass yield - established vendors, standard process

- International cavities from established vendors using established processes
- 2nd pass yield for **>35 MV/m:-**
    - for integrated sample is 57 ± 8%
    - for 2010-2012 alone is 69 ± 13%

C.M. Ginsburg et al., KILC12, Daegu, S. Korea
http://ilcagenda.linearcollider.org/contributionDisplay.py?contribId=85&sessionId=36&confId=5414

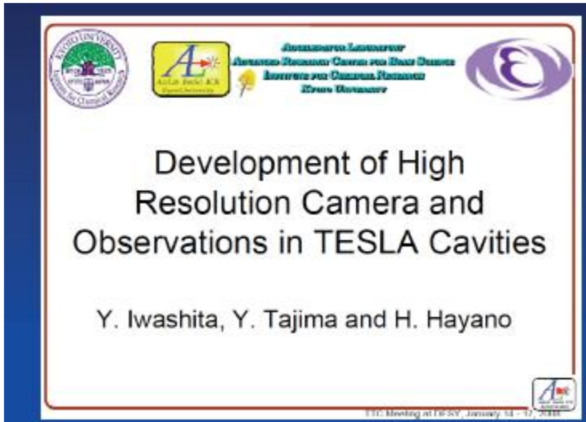
Cavities Bulk-EP at Vendor



RI bulk-EP removal amount (µm)
133 153 138 130 152 140

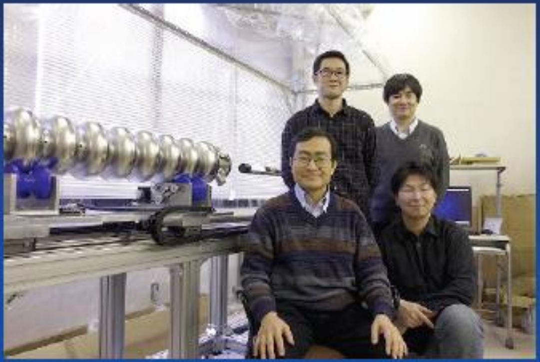
*KEK grinding repair

Optically Detection of Defects



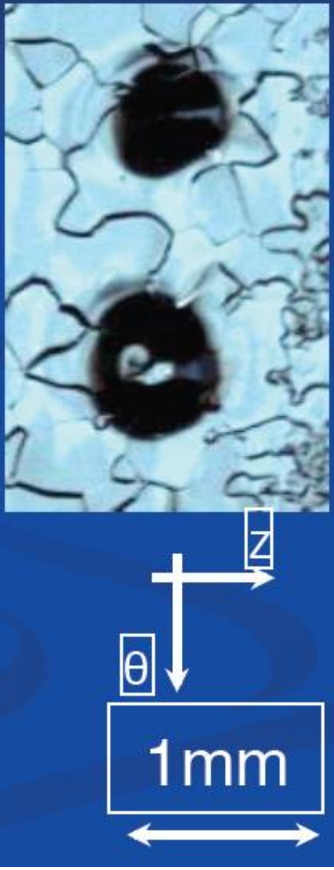
Development of High Resolution Camera and Observations in TESLA Cavities

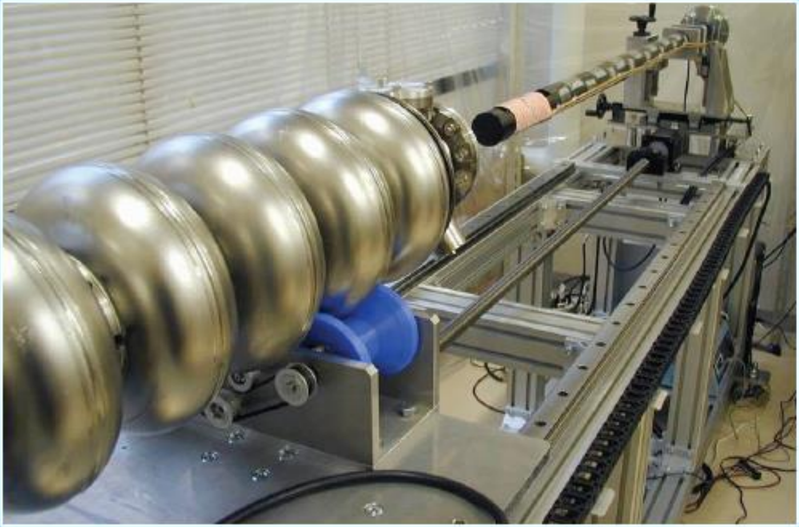
Y. Iwashita, Y. Tajima and H. Hayano



AES001 #3 cell 169°

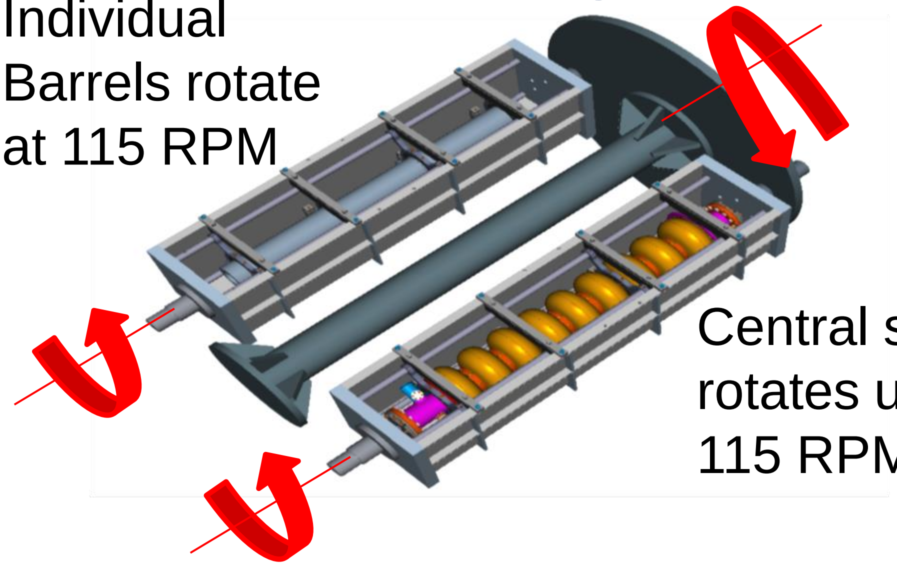
Edge of heat-affected zone





Enables defects that potentially could lead to quenches

Centrifugal Barrel Polishing (CBP)



Individual Barrels rotate at 115 RPM

Central shaft rotates up to 115 RPM

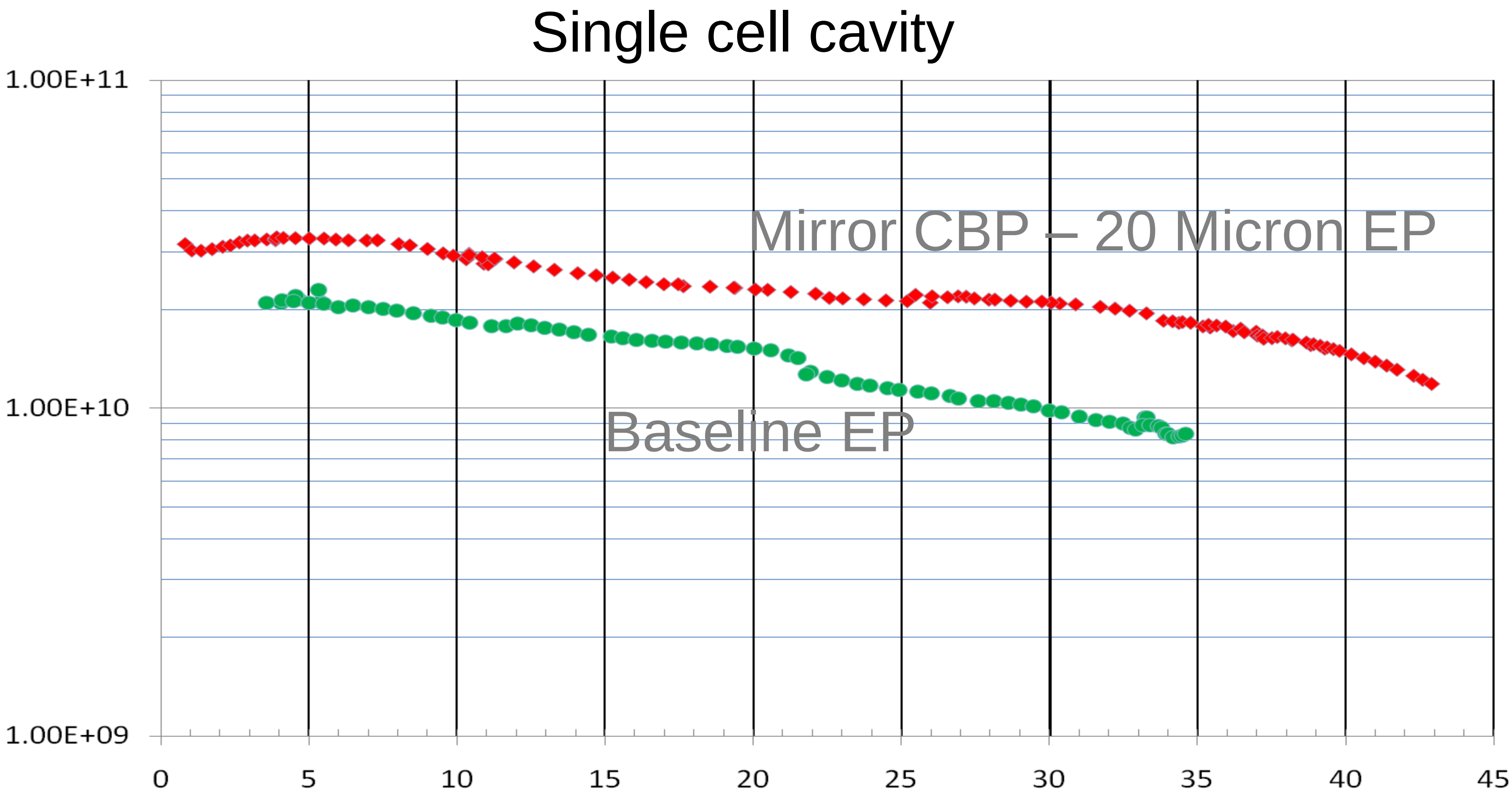
Soap

Colloidal silica

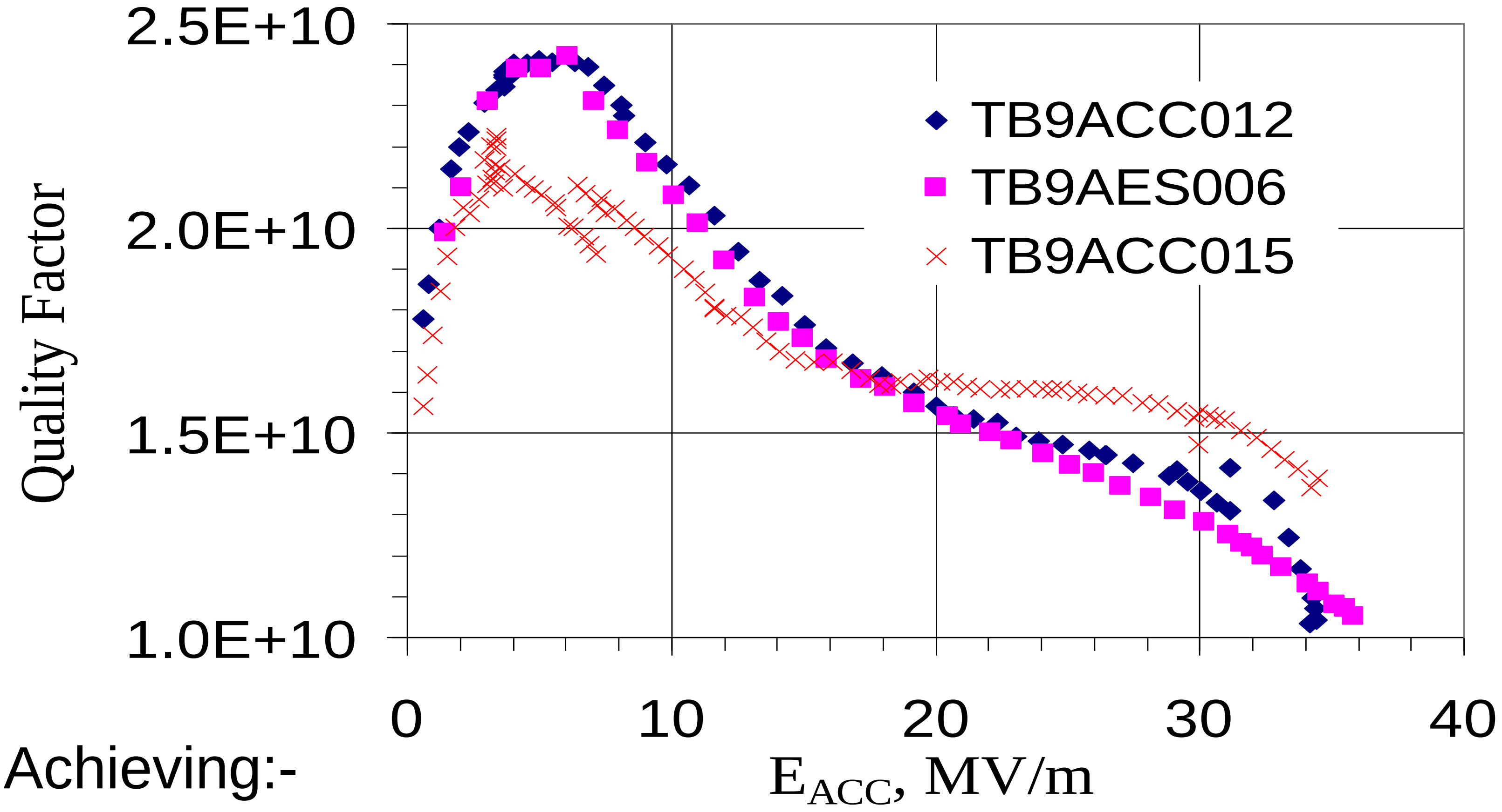
Inclusion not removed by EP, completely removed by CBP

C Cooper, FNAL

CBP – Single Cell Tests



CBP – 9-Cell Tests



Achieving:-

- Higher gradients
- Higher Qs
- Improved yields

SC Thin Films

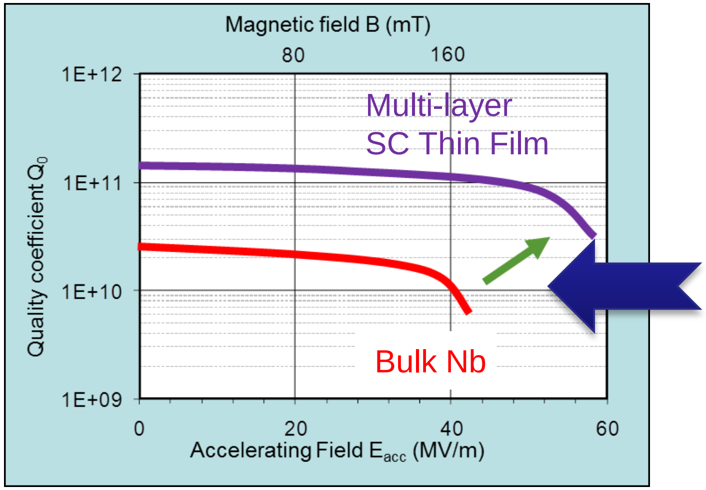
Potential breakthrough

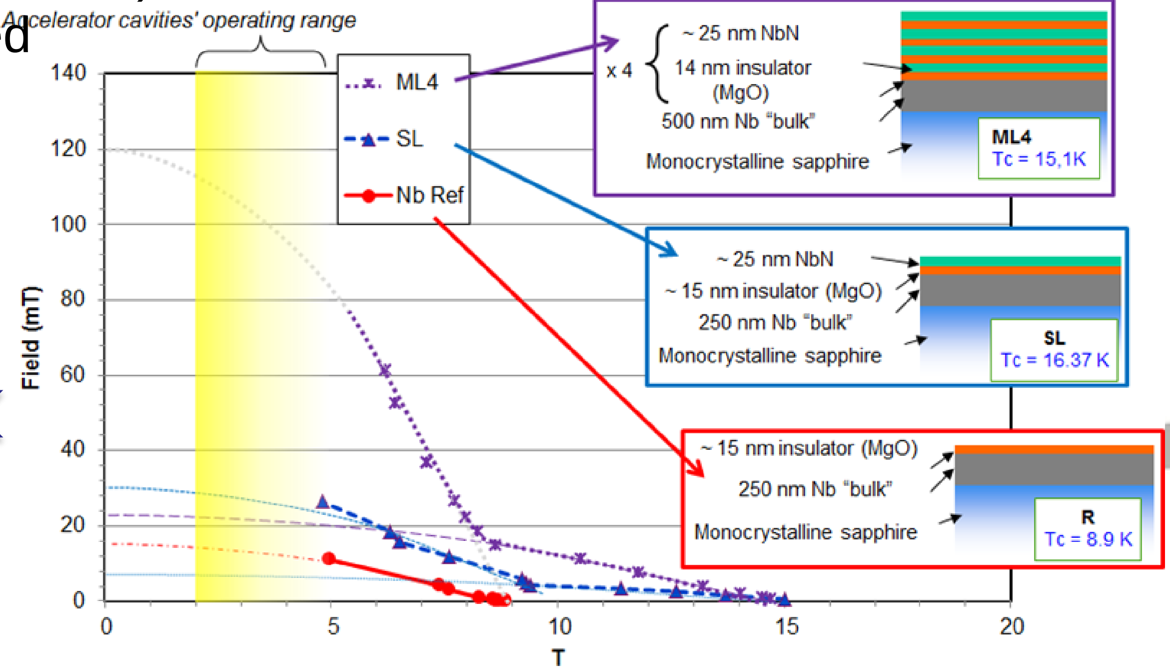
Niobium on copper (µm):

- New revolutionary deposition techniques developed:
  - HIPIMS, CVD, ALD
- Great expectations in cost reduction
- Improved performance c.f. bulk Nb

Higher Tc material (nm), multilayer:

- Trapped vortices model (Gurevich)
- Higher field and Qo expected





http://eucard2.web.cern.ch/activities/wp12-innovative-radio-frequency-rf-technologies

Wheelhouse

Summary

- Higher gradients are being achieved through improved design optimisation and a better understanding of dc and RF breakdown
- Material studies are being examined to push gradients higher
- Great gains have been made through the optimisation of processes
- Industrial and laboratory partnerships have successfully aided the development of technology capabilities
- The RF technology choice is based upon cost effective delivery for a specific application
- The chosen technology limitations must be overcome in order to be reliably compliant

Thank you for your attention