2005 International Workshop-Summer School
on physics, detector and accelerator at the linear collider
July 15-20, 2005

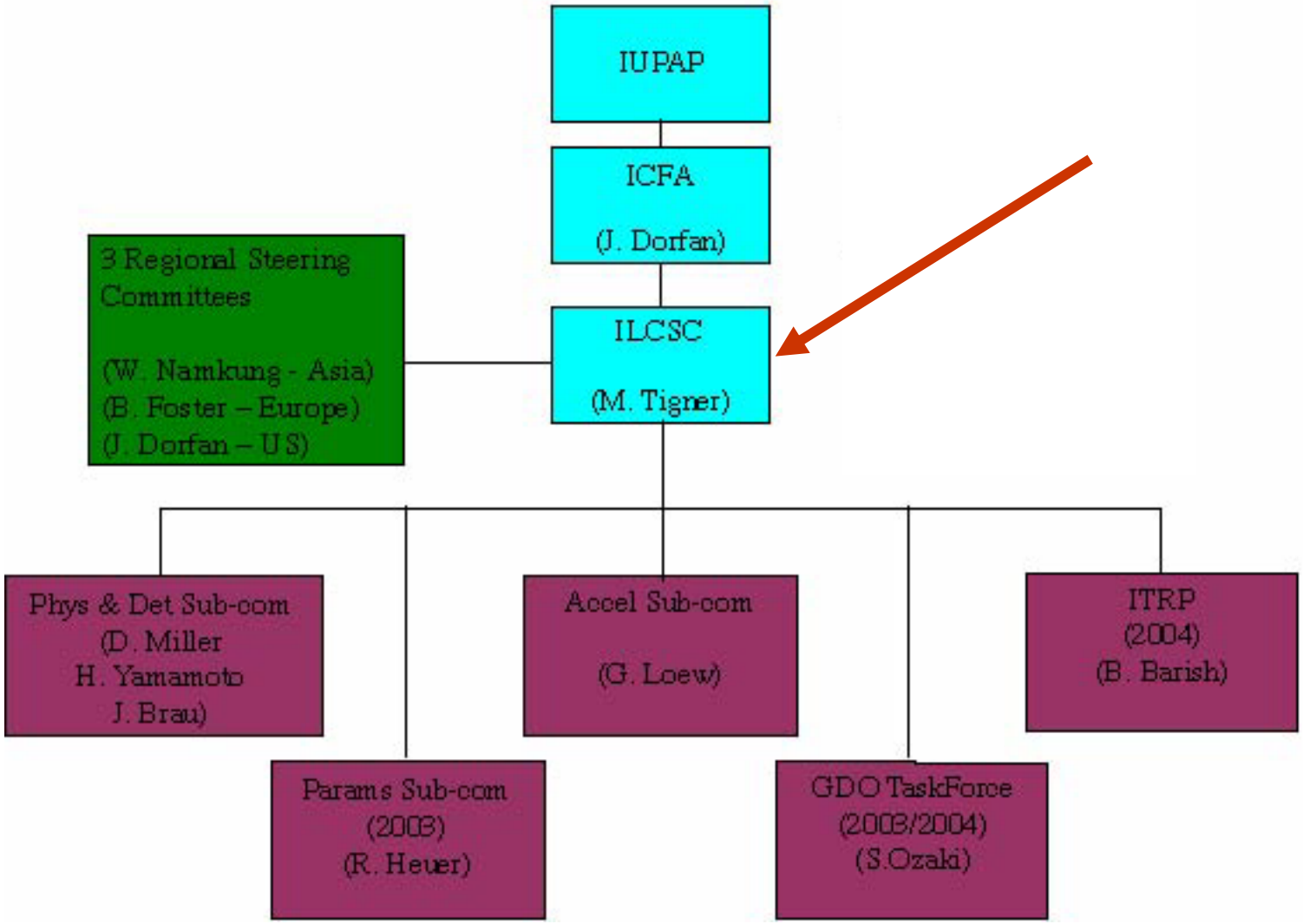
Center for High Energy Physics
Tsinghua University, Beijing 100084, China

Lecture 3

"Cold" Choice and Superconducting RF

Carlo Pagani
INFN Milano and DESY
On leave from University of Milano

LC Organisation up to August 2004



ILCSC as in 2002

International Linear Collider Steerng Committee

Membership of the ILCSC in 2002

H. Chen (IHEP, Beijing)
J. Dorfan (SLAC)
B. Foster (Bristol, UK)
C. Garcia Canal (La Plata, Argentina)
P. Grannis (Stony Brook, US)
S. Komamiya (Tokyo)
L. Maiani (CERN)
D. Miller (UCL, UK)
W. Namkung (POSTECH, Korea)
A. Skrinsky (BINP)
H. Sugawara (KEK)
M. Tigner (Cornell) – Chair
Y. Totsuka (Tokyo)
A. Wagner (DESY)
M. Witherell (Fermilab)

First proposed on Feb. 2002 (J. Dorfan), very active since Aug. 2002

Extract from the mandate of the ILCSC

- Engage in outreach, explaining the intrinsic scientific and technological importance of the project.
- Based upon the extensive work already done in Asia, Europe and N. America, engage in defining the scientific roadmap, the scope and primary parameters for machine and detector.
- Monitor the machine R&D activities and make recommendations on the coordination and sharing of R&D tasks as appropriate.
- Identify models of the organizational structure, based on international partnerships, adequate for constructing the LC facility.
- Carry out such other tasks as may be approved or directed by ICFA.

Technology Choice: NLC/JLC or TESLA

The International Linear Collider Steering Committee (ILCSC) selected the twelve members of the International Technology Recommendation Panel (**ITRP**) at the end of 2003:

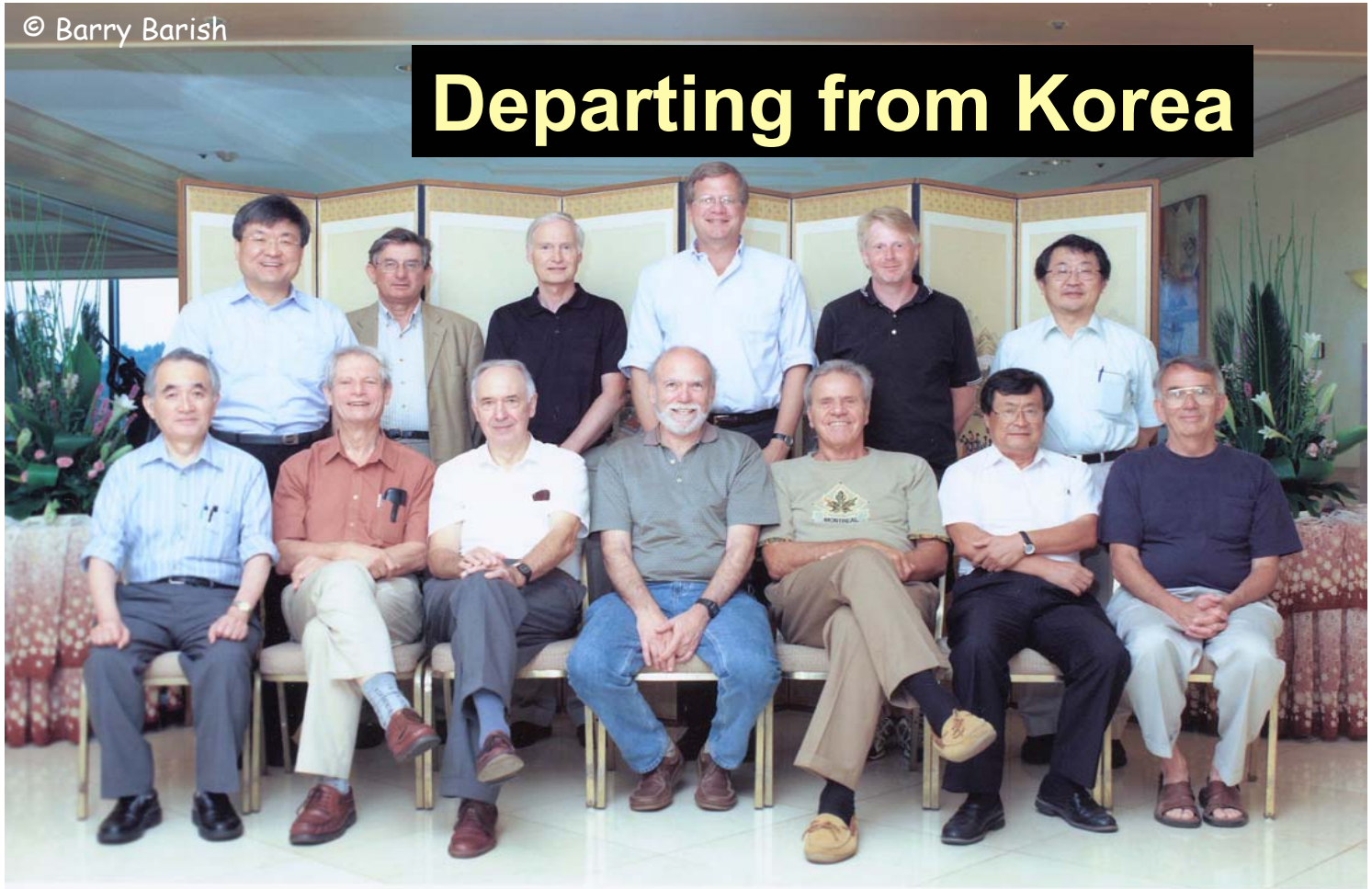
Asia:	**Europe:**	**North America:**
G.S. Lee	J-E Augustin	J. Bagger
A. Masaike	G. Bellettini	**B. Barish (Chair)**
K. Oide	G. Kalmus	P. Grannis
H. Sugawara	V. Soergel	N. Holtkamp

First meeting end of January 2004 at RAL

Mission: one technology by end 2004

Result: recommendation on 19 August 2004

ITRP after the Last Meeting



International Technology Recommendation Panel Meeting
August 11 ~ 13, 2004. Republic of Korea

From the ILC Birthday

Why ITRP?

- Two parallel developments over the past few years (the science & the technology)
- The precision information from LEP and other data have pointed to a low mass Higgs; Understanding electroweak symmetry breaking, whether supersymmetry or an alternative, will require precision measurements.
- There are strong arguments for the complementarity between a ~0.5-1.0 TeV LC and the LHC science.
- Designs and technology demonstrations have matured on two technical approaches for an e^+e^- collider that are well matched to our present understanding of the physics. (We note that a C-band option could have been adequate for a 500 GeV machine, if NLC/GLC and TESLA were not deemed mature designs).

© Barry Barish

From the ILC Birthday

Why Decide Technology Now?

- We have an embarrassment of riches !!!!
  - Two alternate designs -- "warm" and "cold" have come to the stage where the show stoppers have been eliminated and the concepts are well understood.
  - R & D is very expensive (especially D) and to move to the "next step" (being ready to construct such a machine within about 5 years) will require more money and a concentration of resources, organization and a worldwide effort.
  - It is too expensive and too wasteful to try to do this for both technologies.
  - A major step toward a decision to construct a new machine will be enabled by uniting behind one technology, followed by a making a final global design based on the recommended technology.
  - The final construction decision in ~5 years will be able to fully take into account early LHC and other physics developments.

© Barry Barish

From the ILC Birthday

The Charge to the International Technology Recommendation Panel

General Considerations

The International Technology Recommendation Panel (the Panel) should recommend a Linear Collider (LC) technology to the International Linear Collider Steering Committee (ILCSC).

On the assumption that a linear collider construction commences before 2010 and given the assessment by the ITRC that both TESLA and JLC-X/NLC have rather mature conceptual designs, the choice should be between these two designs. If necessary, a solution incorporating C-band technology should be evaluated.

Note -- We have interpreted our charge as being to recommend a technology, rather than choose a design

© Barry Barish

19-Aug-04 ITRP - LC Technology Recommendation 8

From the ILC Birthday

Evaluating the Criteria Matrix

- **We analyzed the technology choice through studying a matrix having six general categories with specific items under each:**
  - the scope and parameters specified by the ILCSC;
  - technical issues;
  - cost issues;
  - schedule issues;
  - physics operation issues;
  - and more general considerations that reflect the impact of the LC on science, technology and society

- **We evaluated each of these categories with the help of answers to our "questions to the proponents," internal assignments and reviews, plus our own discussions**

© Barry Barish

From the ILC Birthday

The Recommendation

- **We recommend that the linear collider be based on superconducting rf technology (from Exec. Summary)**
  - This recommendation is made with the understanding that we are recommending a technology, not a design. We expect the final design to be developed by a team drawn from the combined warm and cold linear collider communities, taking full advantage of the experience and expertise of both (from the Executive Summary).
  - We submit the Executive Summary today to ILCSC & ICFA
  - Details of the assessment will be presented in the body of the ITRP report to be published around mid September
  - The superconducting technology has features that tipped the balance in its favor. They follow in part from the low rf frequency.

© Barry Barish

From the ILC Birthday

Some of the Features of SC Technology

- The large cavity aperture and long bunch interval reduce the complexity of operations, reduce the sensitivity to ground motion, permit inter-bunch feedback and may enable increased beam current.
- The main linac rf systems, the single largest technical cost elements, are of comparatively lower risk.
- The construction of the superconducting XFEL free electron laser will provide prototypes and test many aspects of the linac.
- The industrialization of most major components of the linac is underway.
- The use of superconducting cavities significantly reduces power consumption.

Both technologies have wider impact beyond particle physics. The superconducting rf technology has applications in other fields of accelerator-based research, while the X-band rf technology has applications in medicine and other areas.

© Barry Barish

19-Aug-04 ITRP - LC Technology Recommendation 14

From the ILC Birthday

Remarks and Next Steps

- CLIC, C-Band, GLC/NLC and TESLA researchers have done a fantastic job bringing these technologies to the point where we can move forward toward making a next generation linear collider a reality.
- We especially want to note the importance of the the work that has been done on the warm technology. We need to fully capitalize on the experience from SLC, FFTB, ATF and TTF as we move forward. The range of systems from sources to beam delivery in a LC is so broad that an optimized design can only emerge by pooling the expertise of all participants.
- We endorse the effort now underway to establish an international model for the design, engineering, industrialization and construction of the linear collider. Formulating that model in consultation with governments is an immediate priority. Strong central management will be critical from the beginning.

© Barry Barish

From the ILC Birthday

Remarks and Next Steps

- The linear collider will be designed to begin operation at 500 GeV, with a capability for an upgrade to about 1 TeV, as the physics requires. This capability is an essential feature of the design. Therefore we urge that part of the global R&D and design effort be focused on increasing the ultimate collider energy to the maximum extent feasible. (from Exec Summary)
- A TeV scale electron-positron linear collider is an essential part of a grand adventure that will provide new insights into the structure of space, time, matter and energy. We believe that the technology for achieving this goal is now in hand, and that the prospects for its success are extraordinarily bright. (from Exec Summary)

© Barry Barish

From the Day After

- Robert Aymar (CERN): "A linear collider is the logical next step to complement the discoveries that will be made at the LHC. The technology choice is an important step in the path towards an efficient development of the international TeV linear collider design, in which CERN will participate."
- Yoji Totsuka (KEK): "This decision is a significant step to bring the linear collider project forward. The Japanese high-energy community welcomes the decision and looks forward to participating in the truly global project."
- Jonathan Dorfan (SLAC): "Scientific discovery is the goal. Getting to the physics is the priority. The panel was presented with two viable technologies. We at SLAC embrace the decision and look forward to working with our international partners."
- Similar Declarations from: Albrecht Wagner (DESY), Hesheng Chen (HEP), Michael Witherell (FNAL) et al.

From the ICFA press release, Beijing, 20 August 2005

About Superconducting RF

- Superconducting RF has been developed to efficiently transmit energy to a variety of particle beams
- For the first few decades the maximum usable accelerating field has been limited by the allowable technology in term of material production, cavity treatments and handling
- The construction and operation of hundreds of moderate gradient cavities at JLAb for CEBAF and at CERN for LEP II have been the basis for a new level in quality control and industrialization
- Deeper understanding of the limiting factors pushed the technology to be compatible with the new challenging demands
- The TESLA challenge to use SRF as the basic technology for the future TeV e^+e^- Linear Collider impressed the required momentum to move SRF Technology to a new frontier, opening a new era
  - Accelerating fields exceeding **35 MV/m**
  - Quality factor higher then $\mathbf{10^{10}}$

RF Losses in NC and SC Cavities

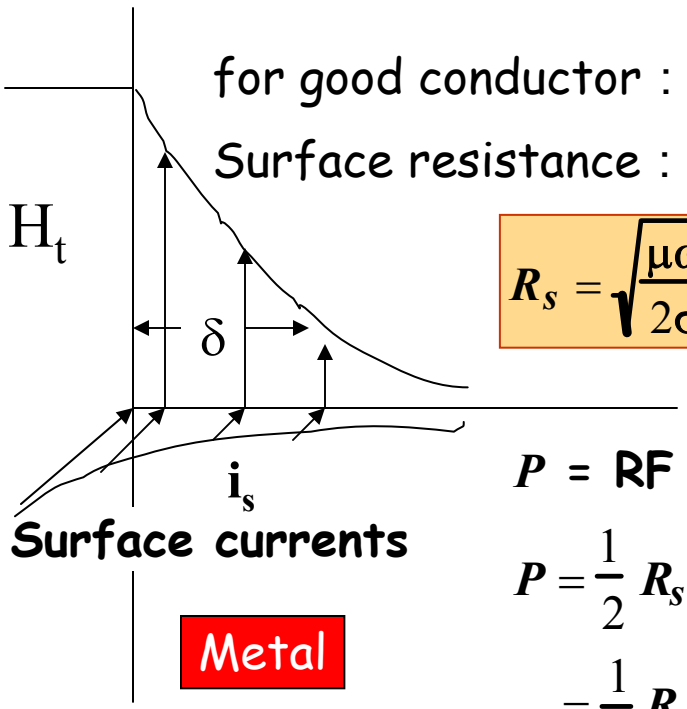
Normal conducting

δ = skin depth of microwave

for good conductor : $\frac{\sigma}{\omega\varepsilon} >> 1$

Surface resistance :

$$R_s = \sqrt{\frac{\mu\omega}{2\sigma}} = \frac{1}{\sigma\delta}$$



P = RF losses

$$P = \frac{1}{2} R_s \int i_s^2 \, ds$$

$$= \frac{1}{2} R_s \int H_s^2 \, ds$$

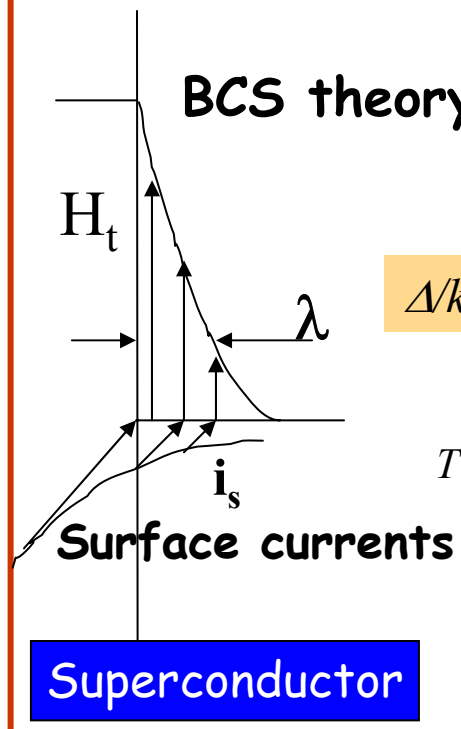
Superconducting

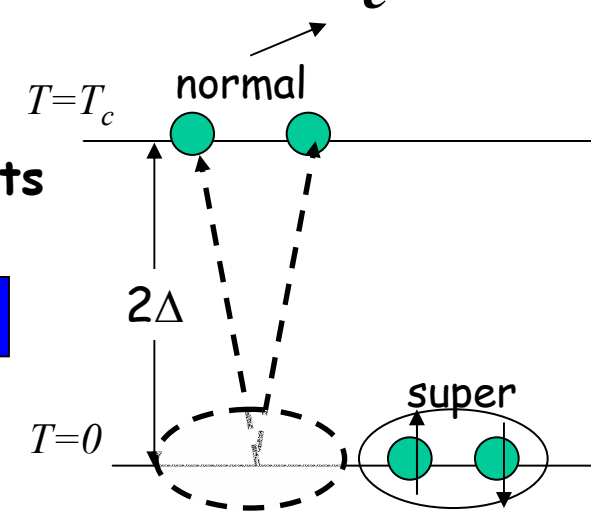
λ = London penetration depth

BCS theory

$$R_s \propto \frac{\omega^2}{T} e^{-\frac{\Delta}{k_B T}}$$

$\Delta/k_B = 1.76\, T_C$



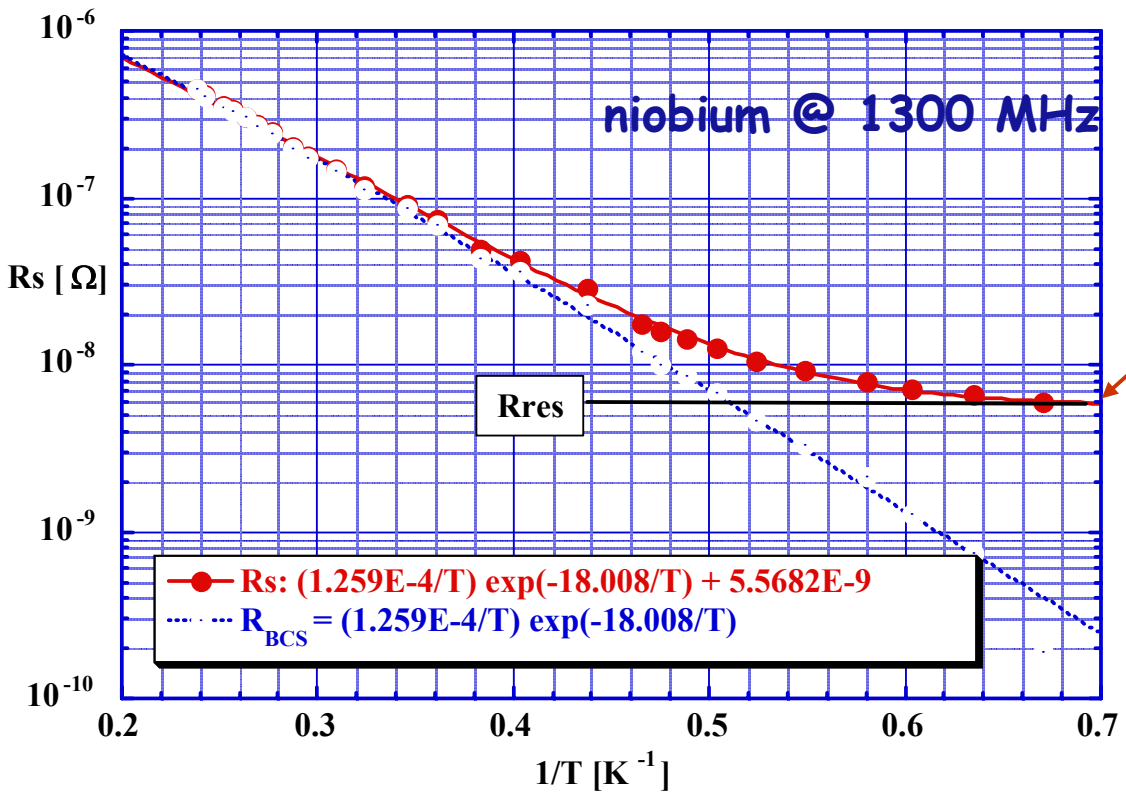


$$Q_0 = \omega U/P = G/R_s$$

The Real Surface Resistance

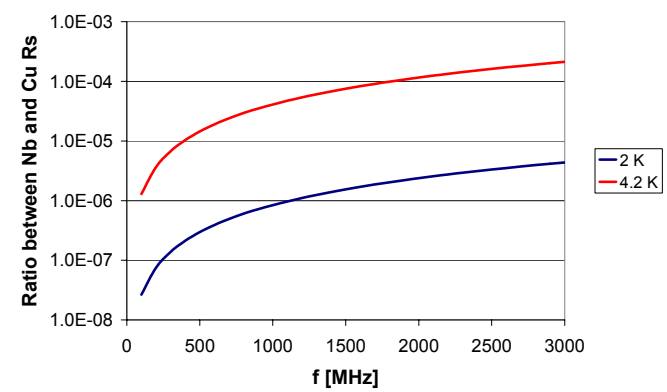
$$R_s = R_{BCS} + R_{res}$$

$$R_{BCS}\,[\mathrm{n}\Omega] = 9 \times 10^{4}\,\frac{f^{2}[\mathrm{GHz}]}{T[\mathrm{K}]}\exp\left(-\frac{17.664}{T[\mathrm{K}]}\right)$$



R_{res}

due to surface defects and residual magnetic field before T_C.



More about Residual Resistance

$$R_s = \frac{A\omega^2}{T}\exp\left(-\frac{\Delta}{k_B T}\right) + R_{res}$$

- Constant R_{res} at $T \rightarrow 0$ for small H_0 is inconsistent with the BCS theory
- Mechanisms of R_{res} are likely unrelated to superconductivity
- Field, temperature and frequency dependences of R_{res} are poorly understood
- Effect of surface oxides (hydrides) or more fundamental mechanisms?

$R_{res} \approx 1\text{-}20\ n\Omega$

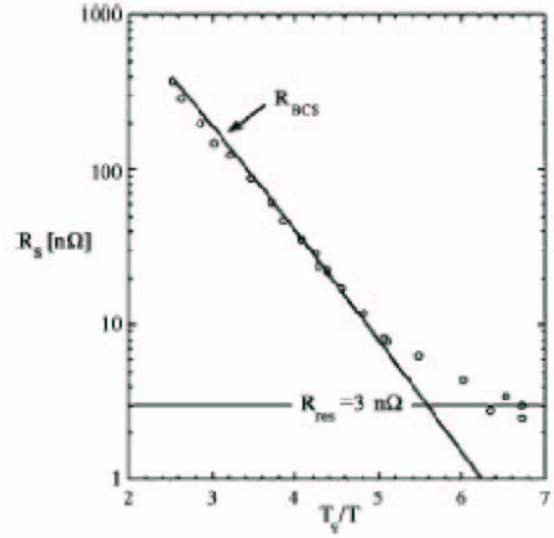
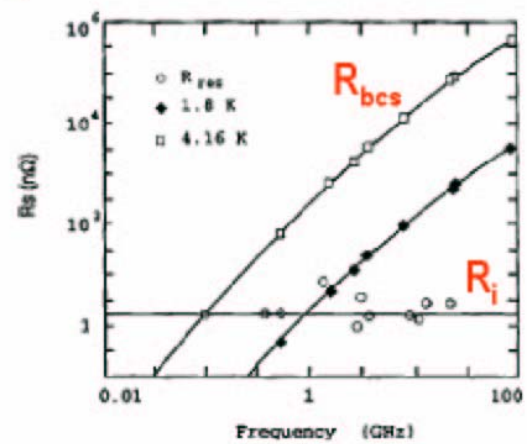
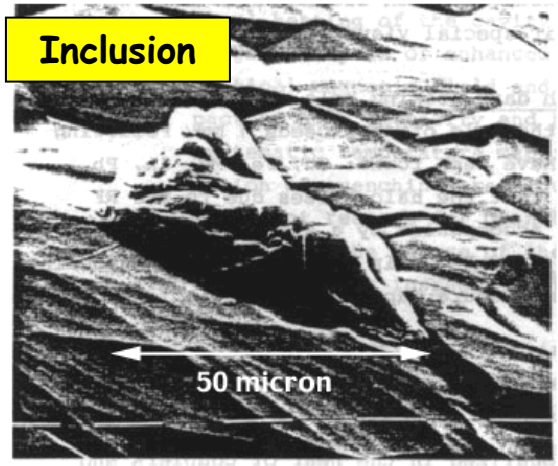


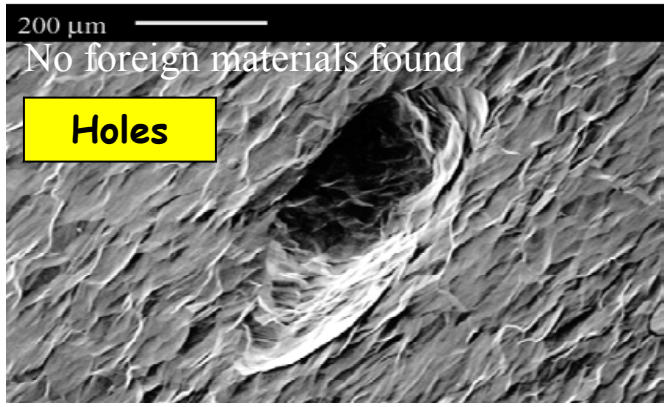
Figure 16. Measured temperature dependence of the surface resistance of a Nb cavity at 1.3 GHz. In this semi-log plot, the linear region gives an energy gap of $\Delta = 1.9kT_c$. The residual resistance is 3 nΩ.

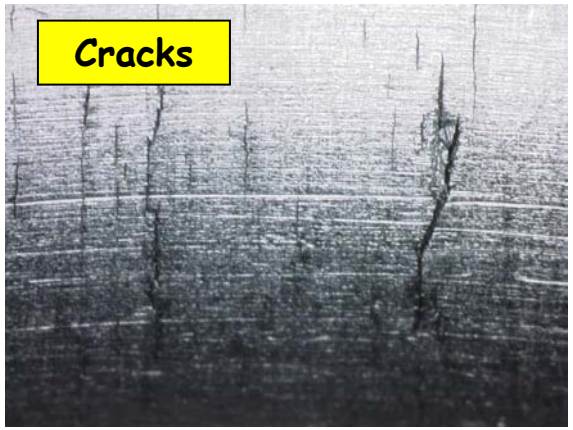


Surface Defects Examples

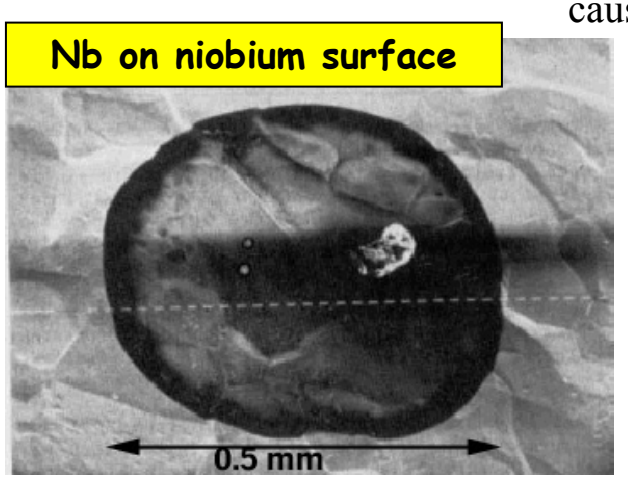
For decades Niobium has been a by-product of Tantalum production

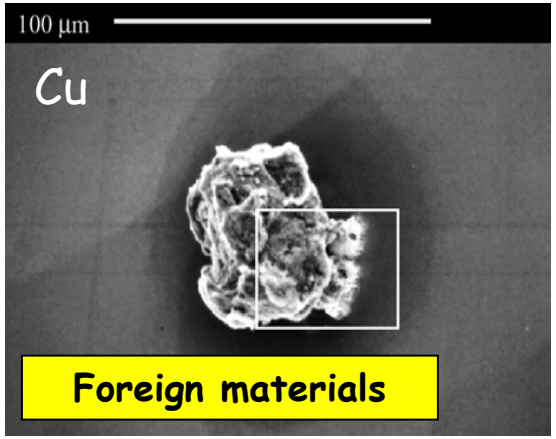


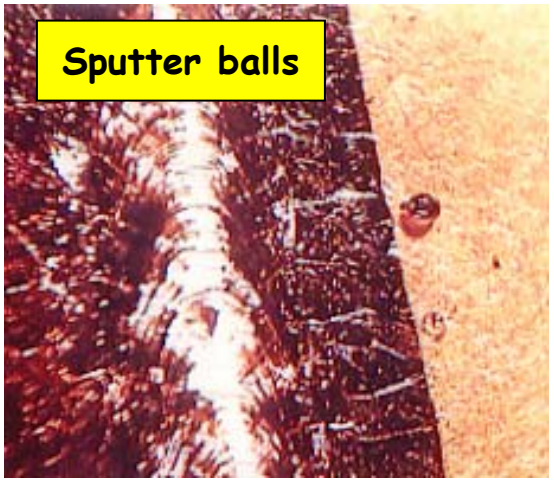




Surface defects, holes can also cause TB







Other Physical Limits

Critical Magnetic Field Limit

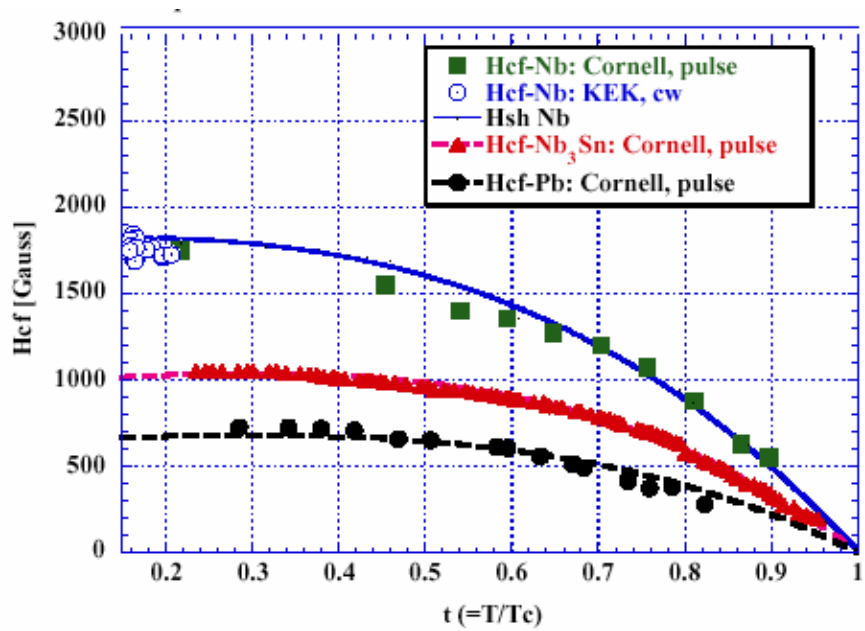
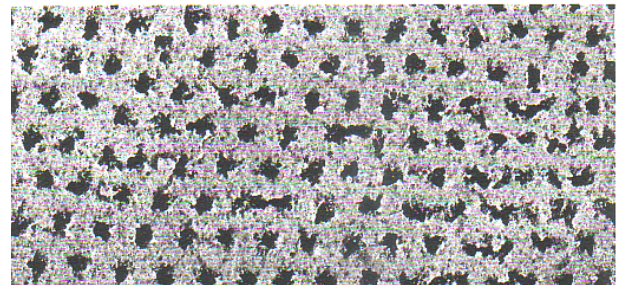


Figure 10: Critical RF fields (Hcf) of sc cavities and Hsh.

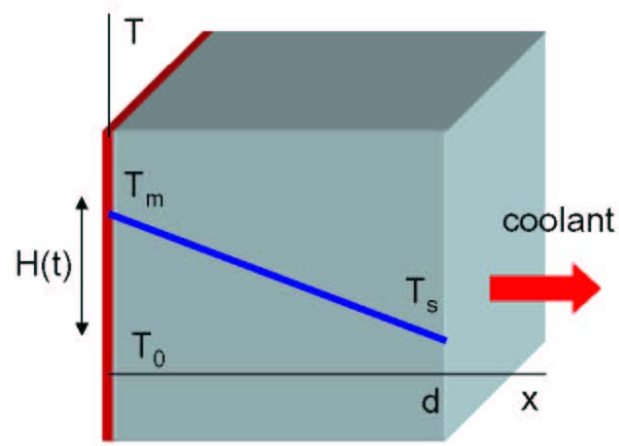
$B_{max} \leq 180$ mT

Vortex state of trapped Magnetic Field



Limited thermal conductivity

- Thermal Conductivity of the bulk Nb
- Kapitza resistance at the surface

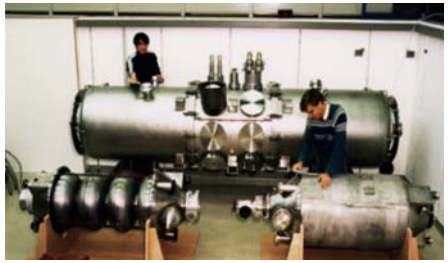


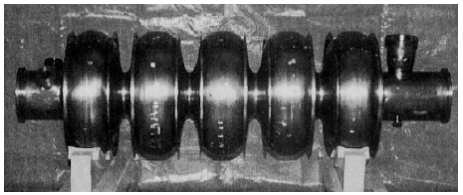
SRF before TESLA

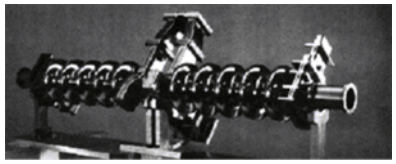
"Livingston Plot" from Hasan Padamnee

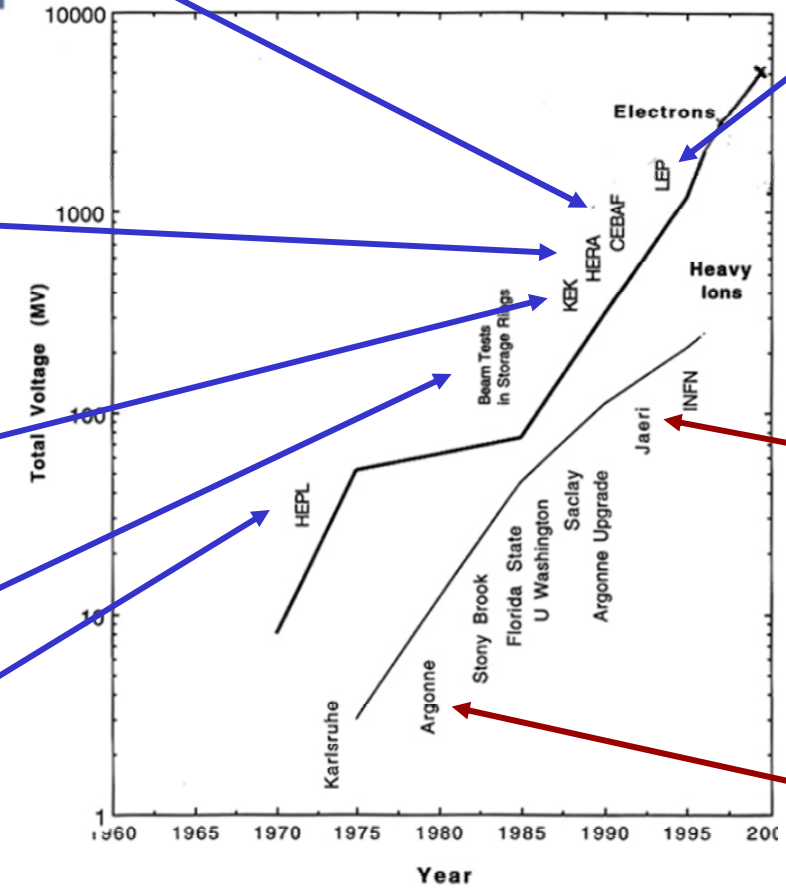
Total Installation > 1000 m

Provided > 5 GV







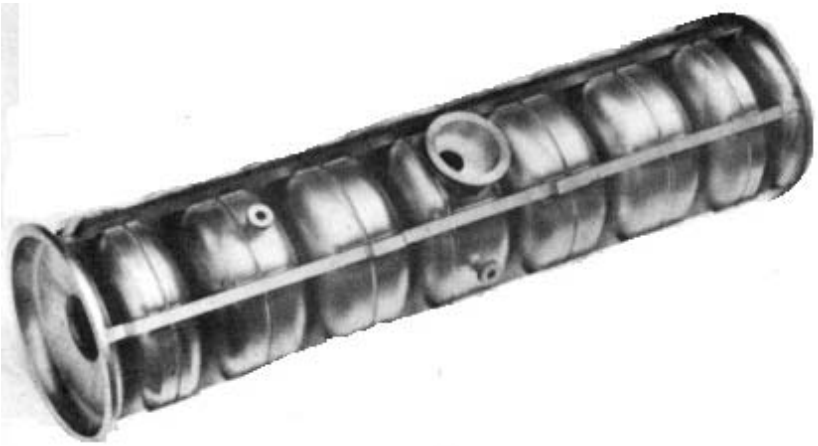


From the pioneering age to 1984

Argonne National Labs

ATLAS: Heavy-ion Linac

- Originated at Caltech
- Implementd and used in other labs for $\beta \sim 0.1$



Stanford University

HEPL: Electron Linac for FEL

- First multicell electron cavity

Limiting Problems

Poor material properties

- Moderate Nb purity (Niobium from the Tantalum production)
- Low Residual Resistance Ratio, RRR → Low thermal conductivity
- Normal Conducting inclusions → Quench at moderate field

Poor cavity treatments and cleanness

- Cavity preparation procedure at the R&D stage
- Poor rinsing and clean room assembly not yet introduced

Microphonics

- Mechanical vibrations in low beta structures → High RF power required

Multipactoring

- Major limit for HEPL and electron linacs to 1984
- Poor codes and surface status

Quenches/Thermal breakdown

- Low RRR and NC inclusions

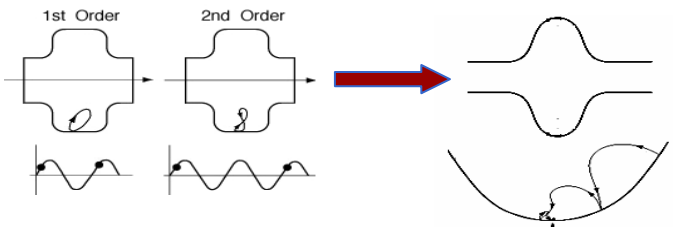
Field Emission

- General limit at those time because of poor cleaning and material defects

R&D waiting for big projects

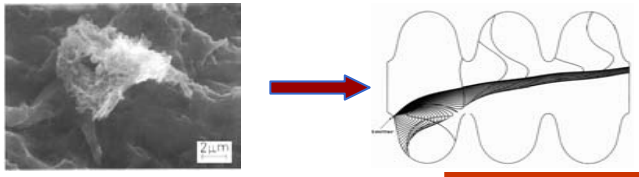
Multipactoring

- A few computer codes developed
- Spherical shape realized at Genova and qualified at Cornell & Wuppertal



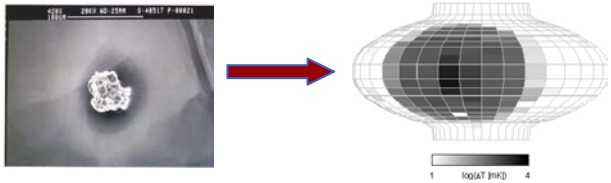
Field Emission

- Emitters were localized and analyzed
- Improved treatments and cleanness

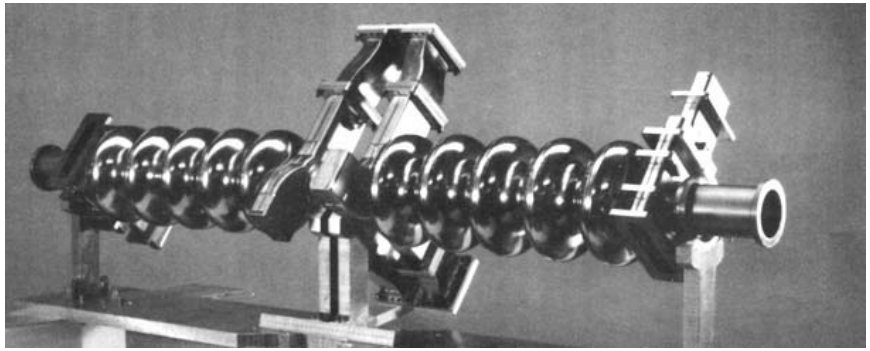


Quenches/Thermal Breakdown

- Higher RRR Nb
- Deeper control for inclusions



E_{acc} > 5 MV/m



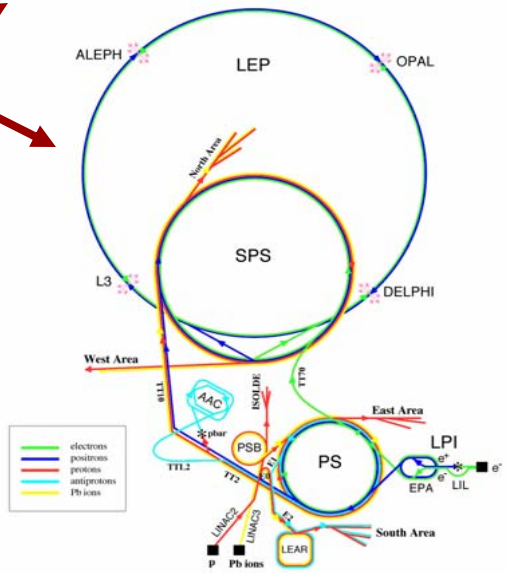
1984/85: First great success

- A pair of 1.5 GHz cavities developed and tested (in CESR) at Cornell
- Chosen for CEBAF at TJNAF for a nominal E_{acc} = 5 MV/m

Exponential grow from middle '80

Multi-cell, β = 1, cavities for large storage rings

- KEK/TRISTAN – (from 1987 to 1989)
  - 200 MV peak RF voltage to the beam per revolution
  - 32 x 5-cell cavities @ 508 MHz
- DESY/HERA – (from 1991 to 1993)
  - 75/30 MV peak RF voltage to the electron beam
  - One string of 16 x 4-cell cavities @ 500 MHz
- CERN/LEP II – (SC upgrade from 1996 to 2000)
  - > 3.65 GV peak RF voltage to the beam per revolution
  - 288 x 4-cell cavities @ 352.2 MHz (256 Sputtered)



Multi-cell, β = 1, cavities for recirculating linacs

- TJNAF/CEBAF – (from 1995 to 1999)
  - 600 MV RF voltage to beam per linac pass
  - 338 x 5-cell cavities @ 1497 MHz RF

Large project impact on SRF technology

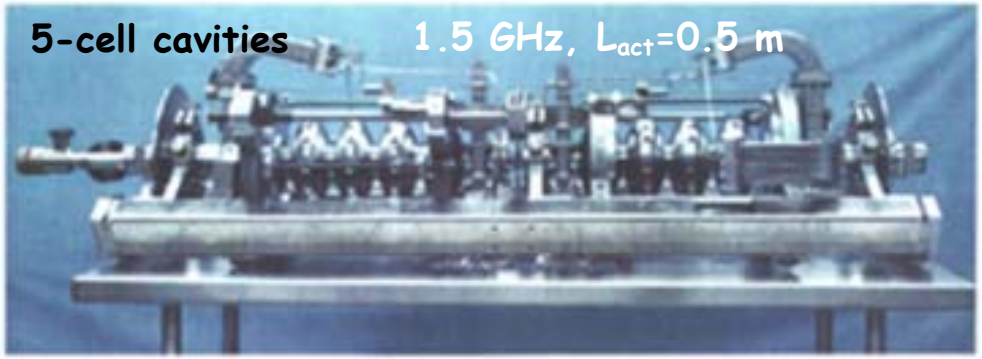
- In 1985 the successful test of a pair of SC cavities in CERS opened the door to the large scale application of SRF for electrons
- The decision of applying this unusual technology in the largest HEP accelerators forced the labs to invest in Research & Development, infrastructures and quality control
- The experience of industry in high quality productions has been taken as a guideline by the committed labs
- At that time TJNAF and CERN played the major role in SRF development, mainly because of the project size
- The need of building hundreds of cavities pushed the labs to transfer to Industry a large part of the production
- The large installations driven by HEP produced a jump in the field
- R&D and basic research on SRF had also a jump thanks to the work of many groups distributed worldwide

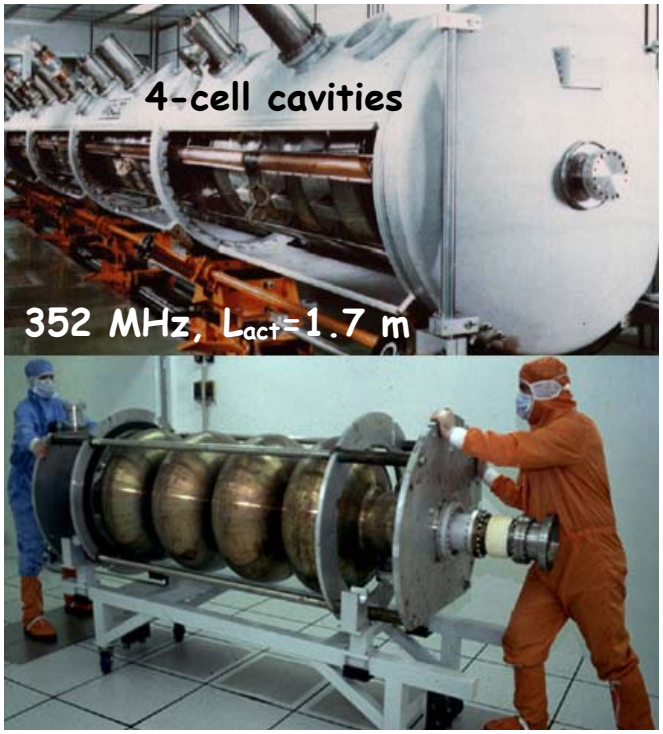
CEBAF and LEP II

CEBAF

338 bulk niobium cavities

- Produced by industry
- Processed at TJNAF in a dedicated infrastructure





LEP II & CERN

32 bulk niobium cavities

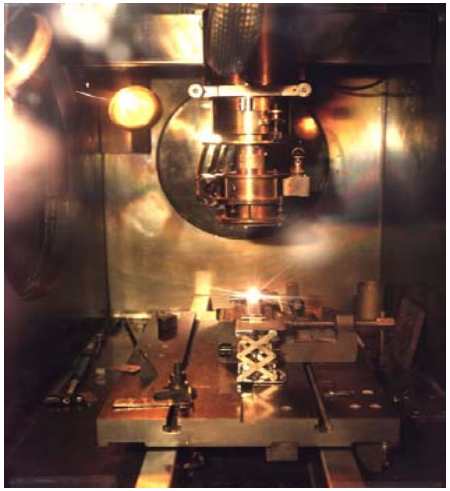
- Limited to 5 MV/m
- Poor material and inclusions

256 sputtered cavities

- Magnetron-sputtering of Nb on Cu
- Completely done by industry
- **Field improved with time**
  $\langle E_{acc} \rangle$ = 7.8 MV/m (Cryo-limited)

Important technological steps

- Use of the best niobium (and copper) allowable in the market at the time
- Industrial fabrication of cavity components with high level quality control
- Assembly of cavity components by Industry via Electron Beam welding in clean vacuum
- Use of ultra pure water for all intermediate cleaning
- Use of close loop chemistry with all parameters specified and controlled
- Cavity completion in Class 100 Clean Room
  - Final cleaning and drying (UV for bacteria and on line resistivity control)
  - Integration of cavity ancillaries



That is

New level on Quality Control

A great success for CEBAF

Processing and conditioning improve cavity performances, when not limited by material defects (hard quench)

- **Field emission moves to higher field**
- **Accelerating Field improves with time**

2 K operation very reliable and well understood

All ancillaries perform quite well

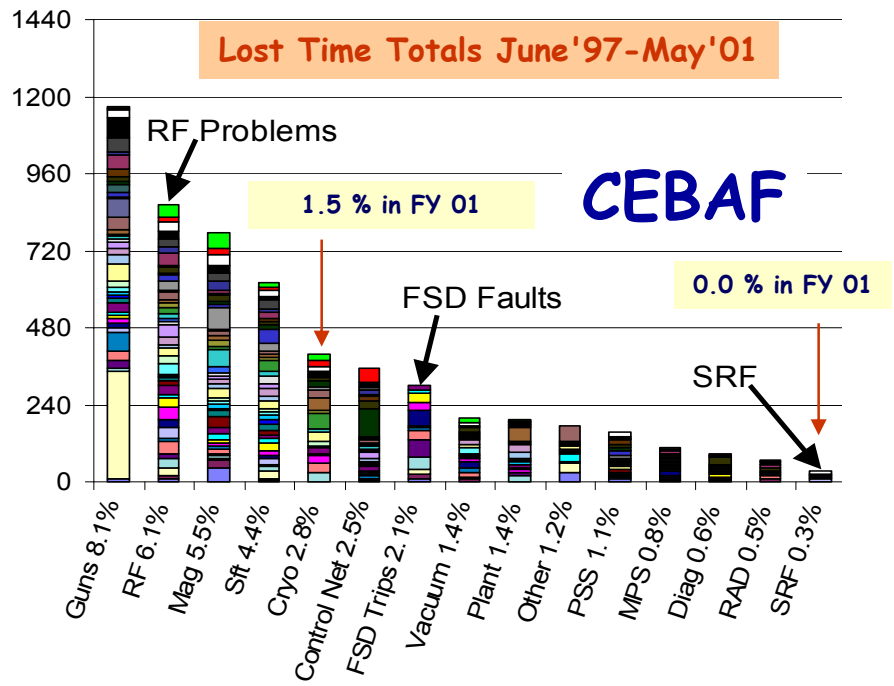
Maximum energy and beam current above the design values

CEBAF performances finally limited by the installed cryo-power and RF-power

Excellent reliability of SRF technology

High availability for physics

The only warm-up for Isabelle Hurricane

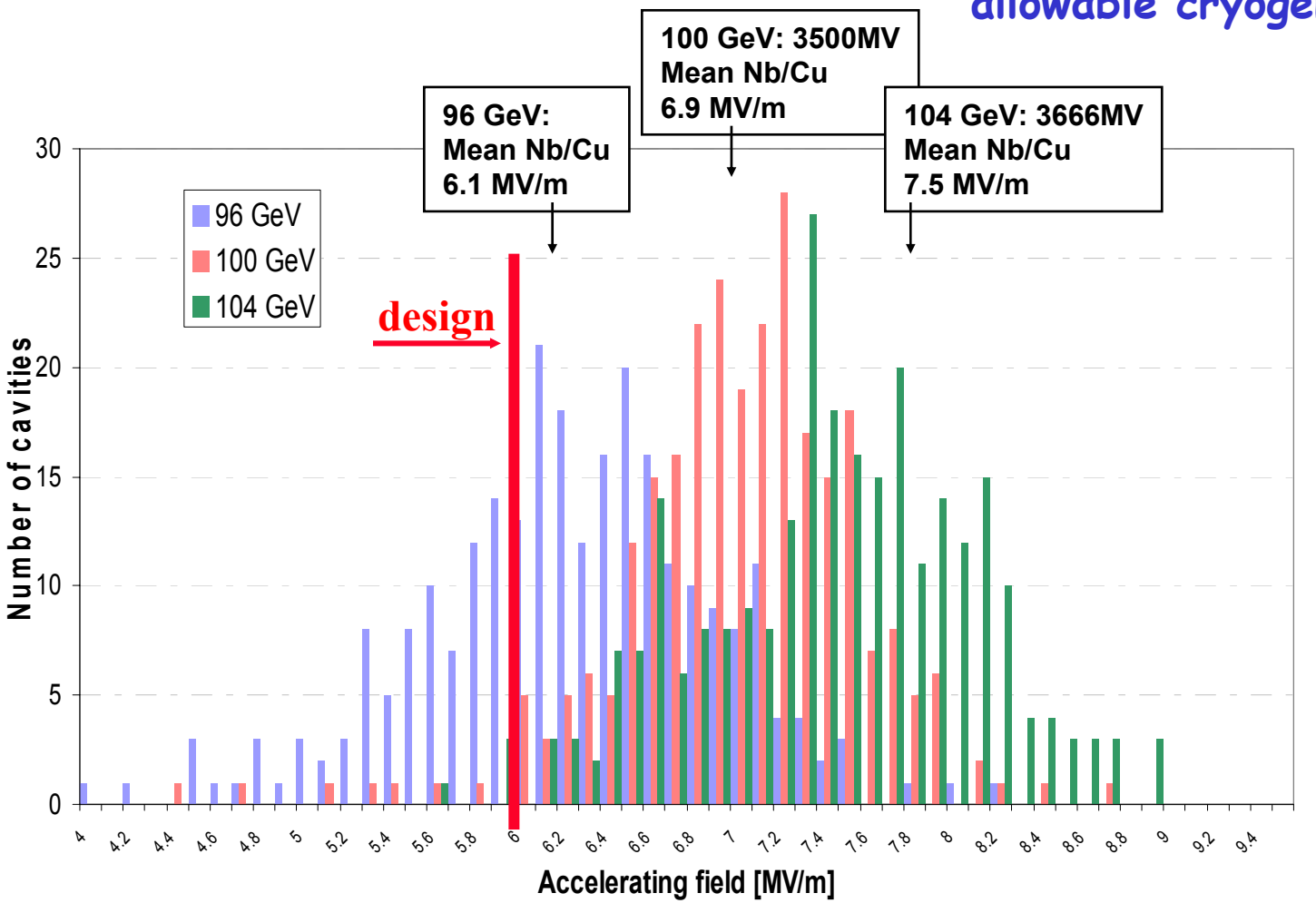


A great success for LEP II

Accelerating Field Evolution with time

from G. Geschonke's Poster for the ITRP visit to DESY

Final energy reach limited by allowable cryogenic power



Same lessons learned

- **Bulk Niobium** is preferred to push **for gradient** and **quality factor**
- Magnetron sputtering looks better in some cases (LHC) when beam current is more important than accelerating field
- **Cryogenics** systems are **highly reliable** and produced by industry
- SRF ancillaries can be designed to be as reliable as the one required by the Normal Conducting RF technology
  - 2 K operation and SRF quality controls end to be a plus
- For high gradient, E_{acc}, and high quality factor, **Q**, **Niobium quality** has to be pushed to the possible limit
- **Quality control** during cavity production and surface processing has to be further improved. High Pressure Rinsing can make the difference
- **Basic R&D** and technological solutions must move together
- When fabrication procedures are fully understood and documented, **Industry** can do as well and possibly better

The TESLA Collaboration

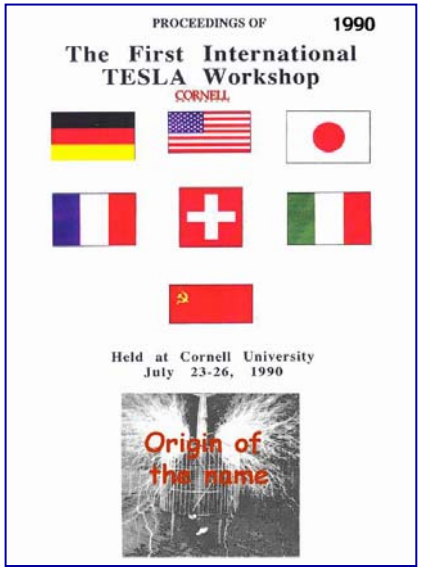
Develop SRF for the future TeV Linear Collider

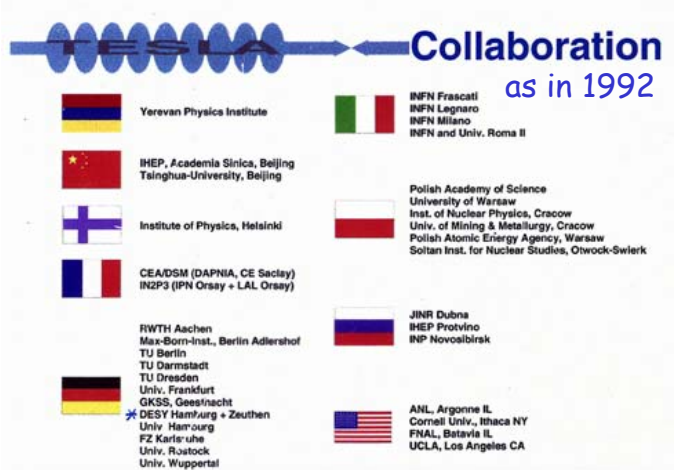
Basic goals

- **Increase gradient by a factor of 5** (Physical limit for Nb at ~ 50 MV/m)
- **Reduce cost per MV by a factor 20** (New cryomodule concept and Industrialization)
- **Make possible pulsed operation** (Combine SRF and mechanical engineering)

Major advantages vs NC Technology

- **Higher conversion efficiency**: more beam power for less plug power consumption
- **Lower RF frequency**: relaxed tolerances and smaller emittance dilution

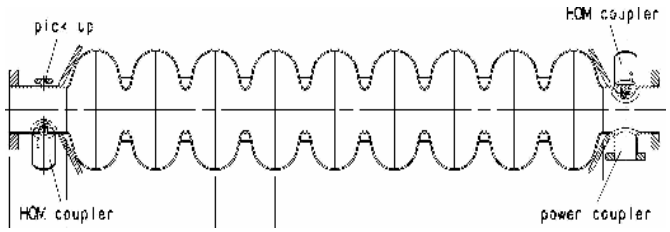




TESLA cavity design and rules

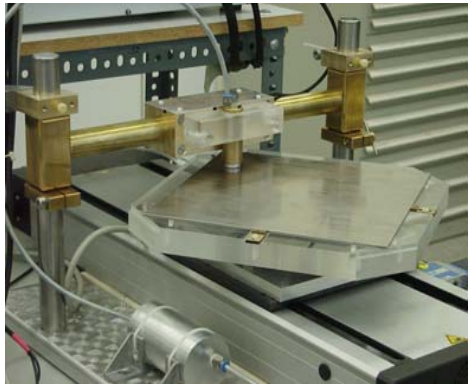
Major contributions from: CERN, Cornell, DESY, CEA-Saclay

- 9-cell, 1.3 GHz



TESLA cavity parameters

R/Q	1036	Ω
E_{peak}/E_{acc}	2.0	
B_{peak}/E_{acc}	4.26	mT/(MV/m)
$\Delta f/\Delta l$	315	kHz/mm
$K_{Lorentz}$	≈ -1	$Hz/(MV/m)^2$



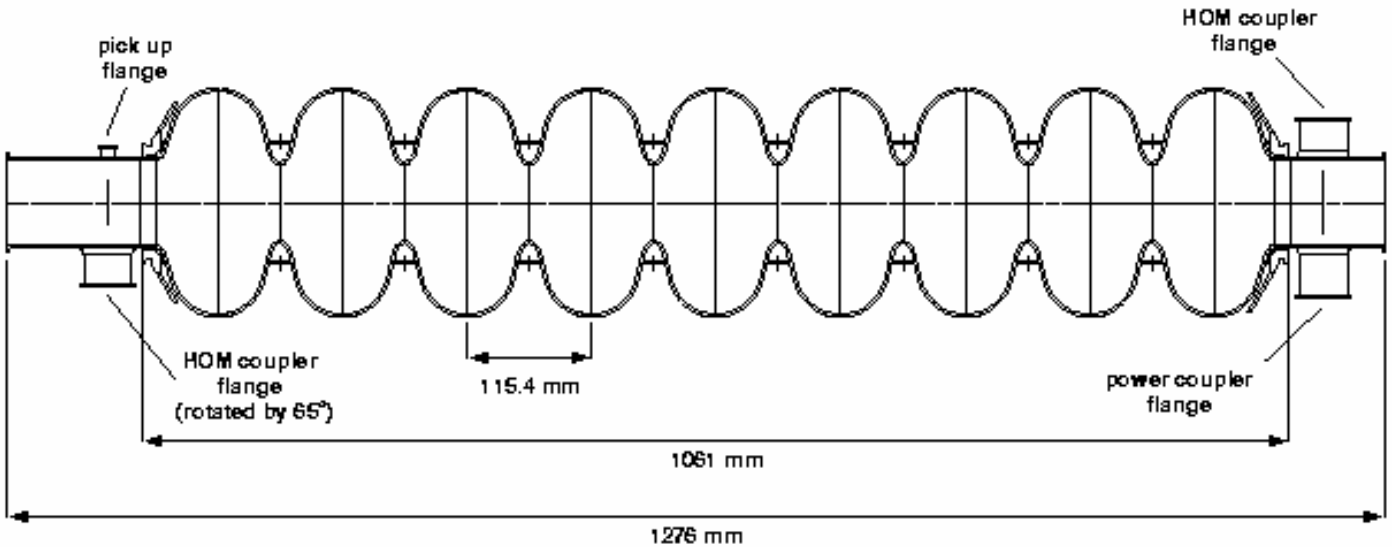
Eddy-current scanning system for niobium sheets

Cleanroom handling of niobium cavities

Preparation Sequence

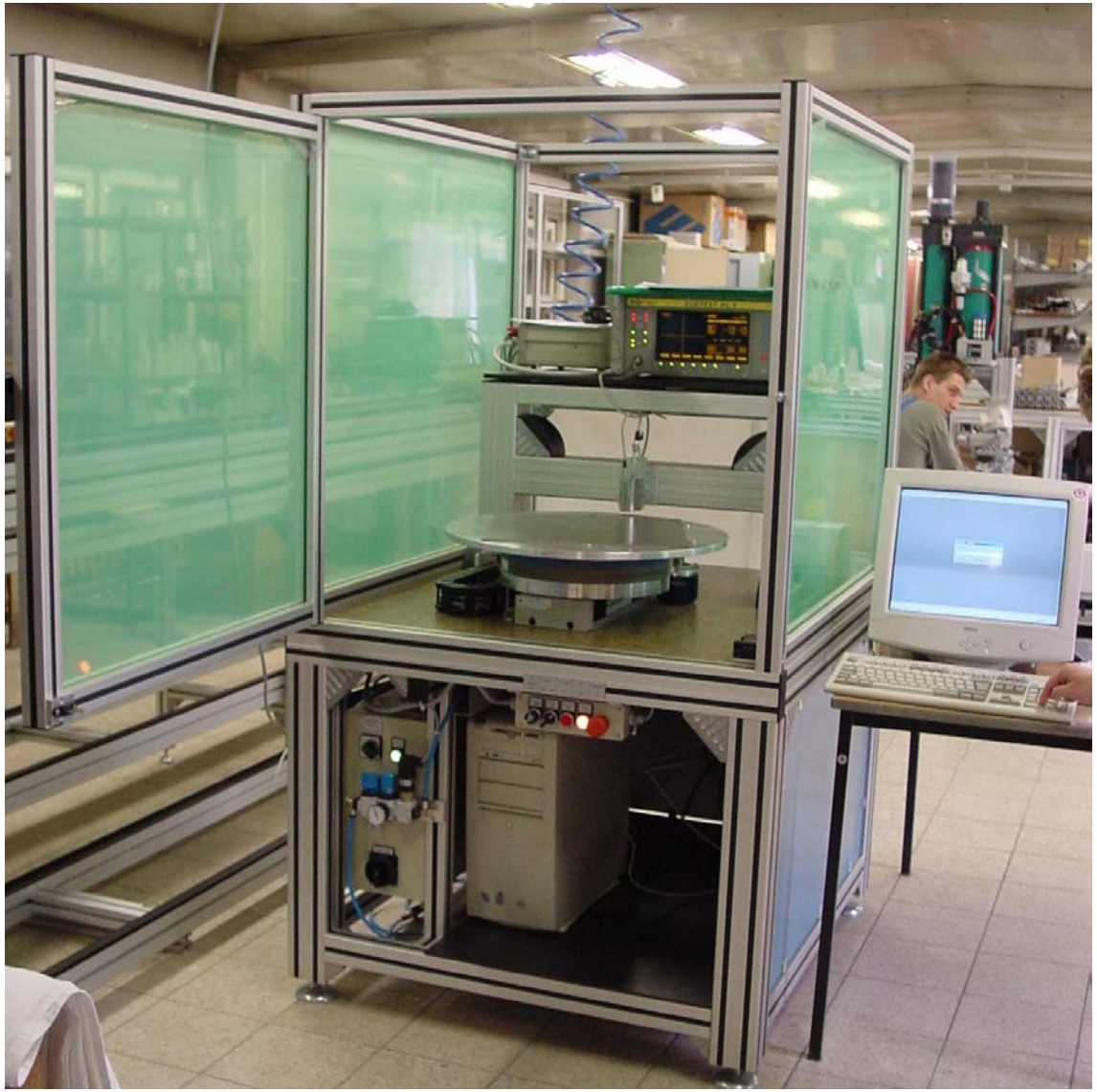
- Niobium sheets (RRR=300) are scanned by eddy-currents to detect avoid foreign material inclusions like tantalum and iron
- Industrial production of full nine-cell cavities:
  - Deep-drawing of subunits (half-cells, etc.) from niobium sheets
  - Chemical preparation for welding, cleanroom preparation
  - Electron-beam welding according to detailed specification
- 800 °C high temperature heat treatment to stress anneal the Nb and to remove hydrogen from the Nb
- 1400 °C high temperature heat treatment with titanium getter layer to increase the thermal conductivity (RRR=500)
- Cleanroom handling:
  - Chemical etching to remove damage layer and titanium getter layer
  - High pressure water rinsing as final treatment to avoid particle contamination

The TESLA 9-cell Cavity

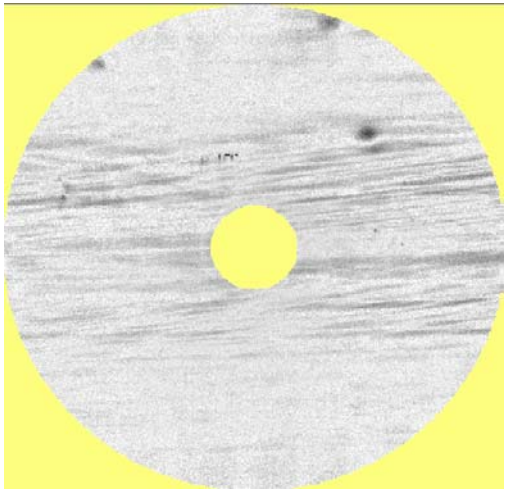


type of accelerating structure	standing wave
accelerating mode	TM0 π mode
fundamental frequency	1300 MHz
design gradient E_{acc} (TTF)	15 MV/m
design gradient E_{acc} (TESLA)	25 MV/m
unloaded quality factor Q_0 (TTF)	$> 3 \times 10^9$
unloaded quality factor Q_0 (TESLA)	$> 5 \times 10^9$
shunt impedance R / Q	1036 Ω
E_{peak} / E_{acc}	2.0
B_{peak} / E_{acc}	4.26 mT / (MV/m)
cavity bandwidth at $Q_0 = 3 \times 10^6$	430 Hz

Eddy Current Scanner for Nb Sheets



Scanning results



- Rolling marks and defects are visible on a niobium disk to be used to print a cavity half-cell.
- Surface analysis is then required to identify the inclusions

Cavity Production: EB welding and QC

High Pressure Water Rinsing

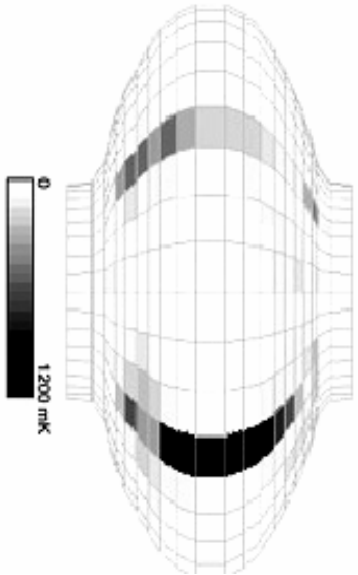
Ultra-pure water (18 MW, partice filter <0.4 mm) is sprayed with a pressure of 100 bar on the niobium surface. This removes particles very efficiently.

HPWR crucial to cure Field Emission

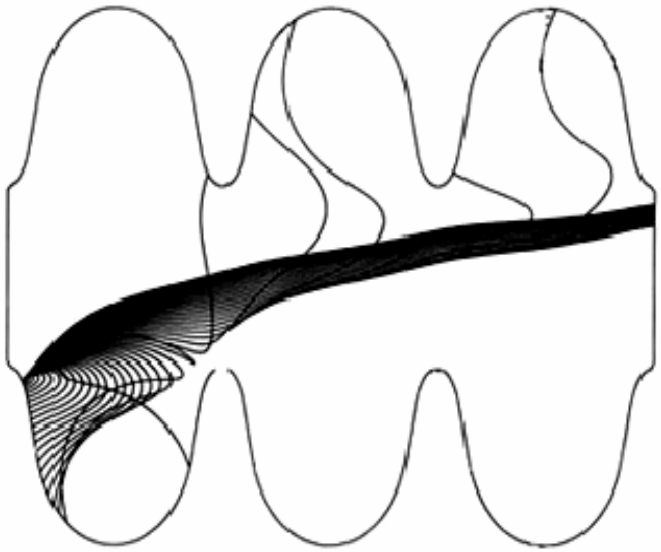
Field emission is normally caused by foreign particle contamination

- Emitted electron current grows exponentially with field
- Reaching the surface accelerated electrons produce cryo-losses and quenches
- Part of the electrons reaches high energies: **Dark Current**

Particle causing field emission



Temperature map of a field emitter



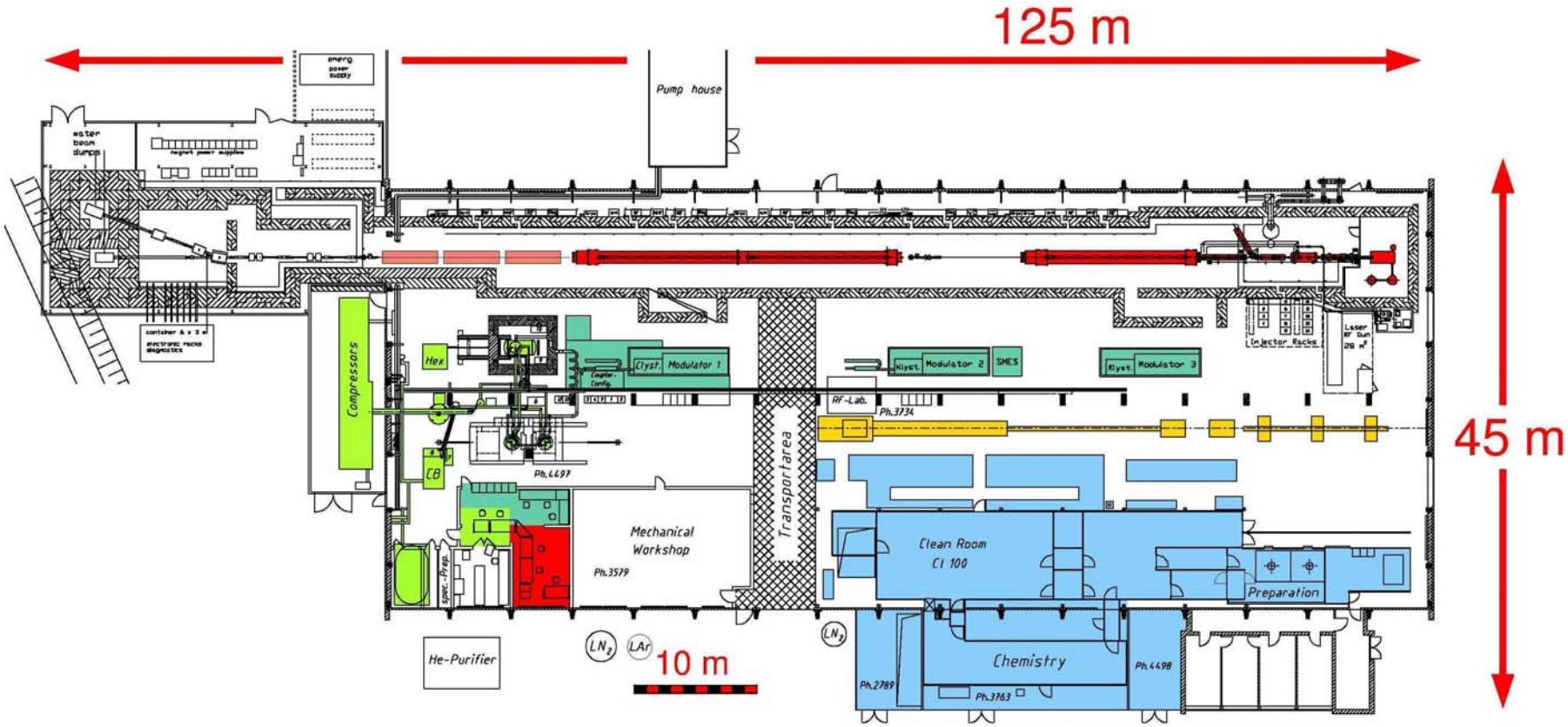
Simulation of electron trajectories in a cavity

Pictures taken from: H. Padamsee, Supercond. Sci. Technol., 14 (2001), R28 –R51

Clean Chemistry and String Assembly

A dedicated new infrastructure at DESY

- Scanning niobium material for inclusion
- Clean closed loop chemistry (Buffer Chemical Polishing – BCP)
- High Pressure Rinsing, HPR, and clean room drying
- Clean Room handling and assembling (Class 10 and 100)

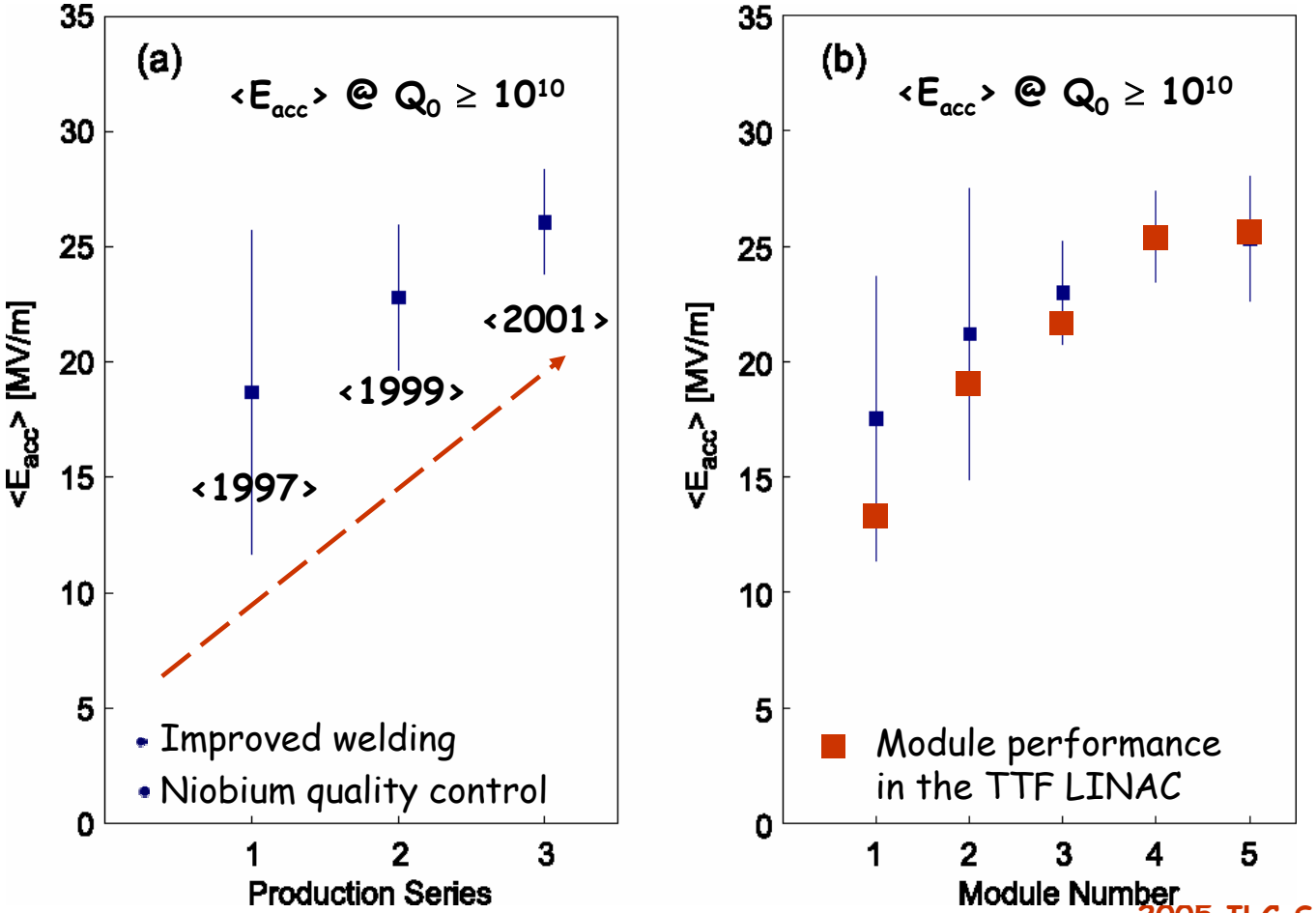


Learning curve with BCP

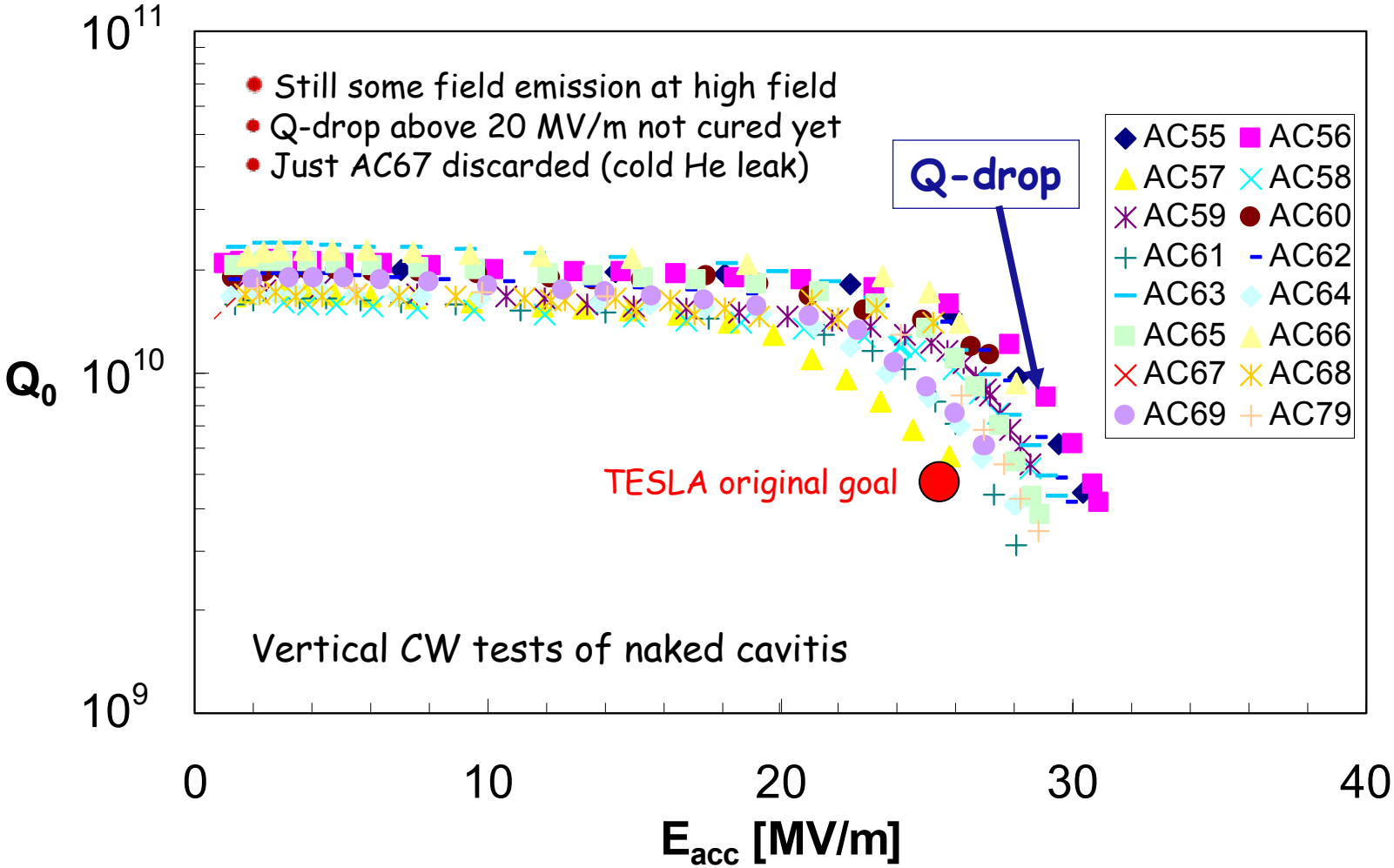
BCP = Buffered Chemical Polishing

3 cavity productions from 4 European industries: Accel, Cerca, Dornier, Zanon

4th production of 30 cavities under way, also to define Quality Control for Industrialization



3rd cavity production with BCP



Two major contributions for high field

- In-Situ Baking (120-140 °C) from CEA-Saclay

  Cures Q-drop at High Field

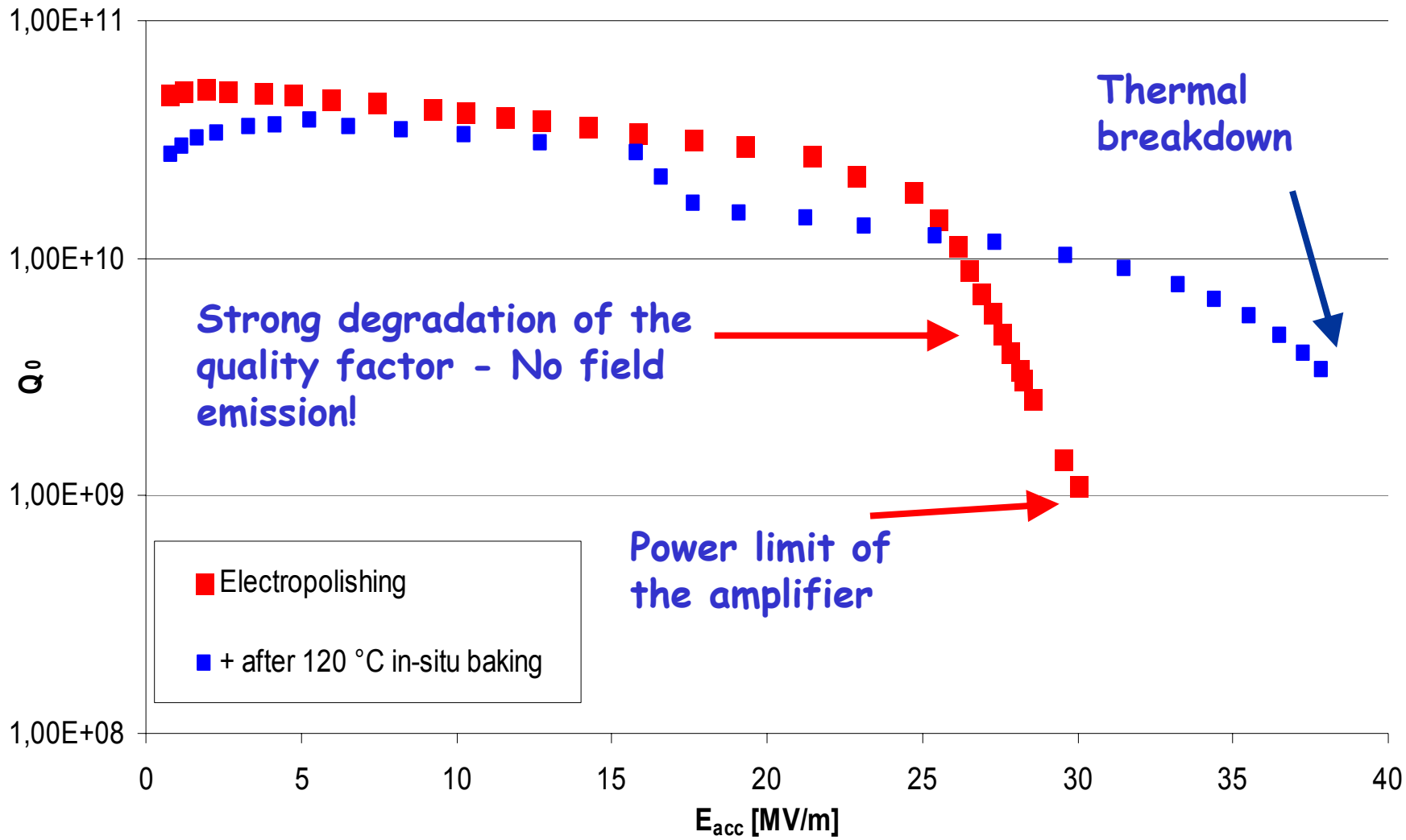
  - Formation of a uniform Nb_2O_5, dielectric, layer on the surface
    - Reduction of the normal conducting dissipation from NbO and NbO_2
  - Diffusion of the high oxygen concentration in the superconducting layer
    - Better BCS performances, i.e. lower surface resistance

- Electro-polishing (EP) from KEK

  Improves field emission and maximum field

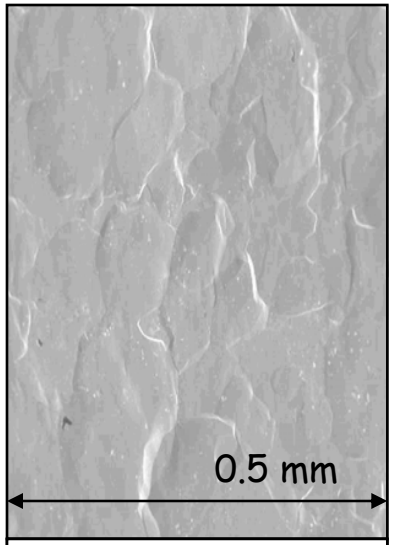
  - Much smoother surface, less local field enhancement
    - Better cleaning with high pressure water rinsing
    - Field emission onset at higher field
    - High temperature (1400 °C) heat treatment possibly avoidable

In-situ Baking effect



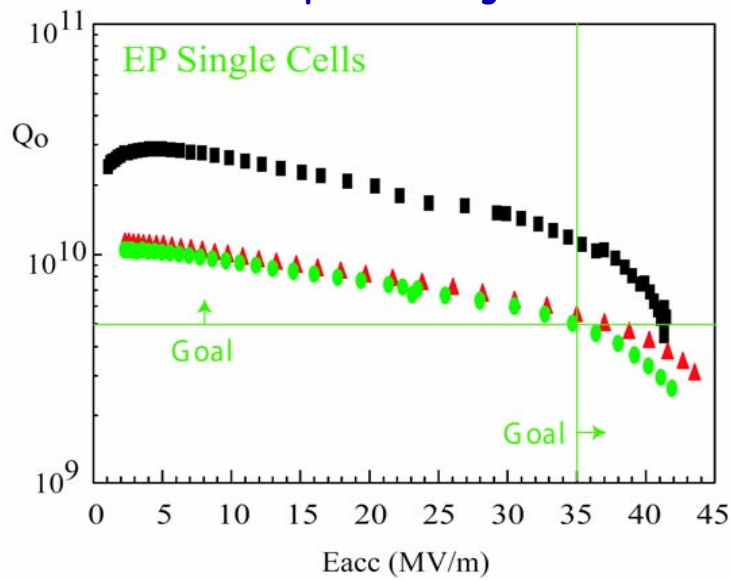
Electro-Polishing for 35 MV/m

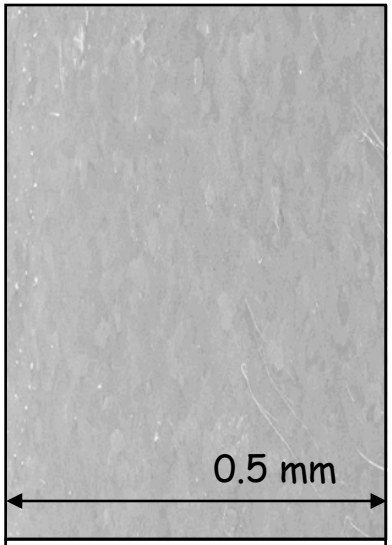
- **EP** developed at KEK by K. Saito (originally by Siemens)
- **Coordinated R&D effort: DESY, KEK, CERN and Saclay**



BCP Surface
(1μm roughness)

First electro-polished single cell cavities





EP Surface
(0.1μm roughness)

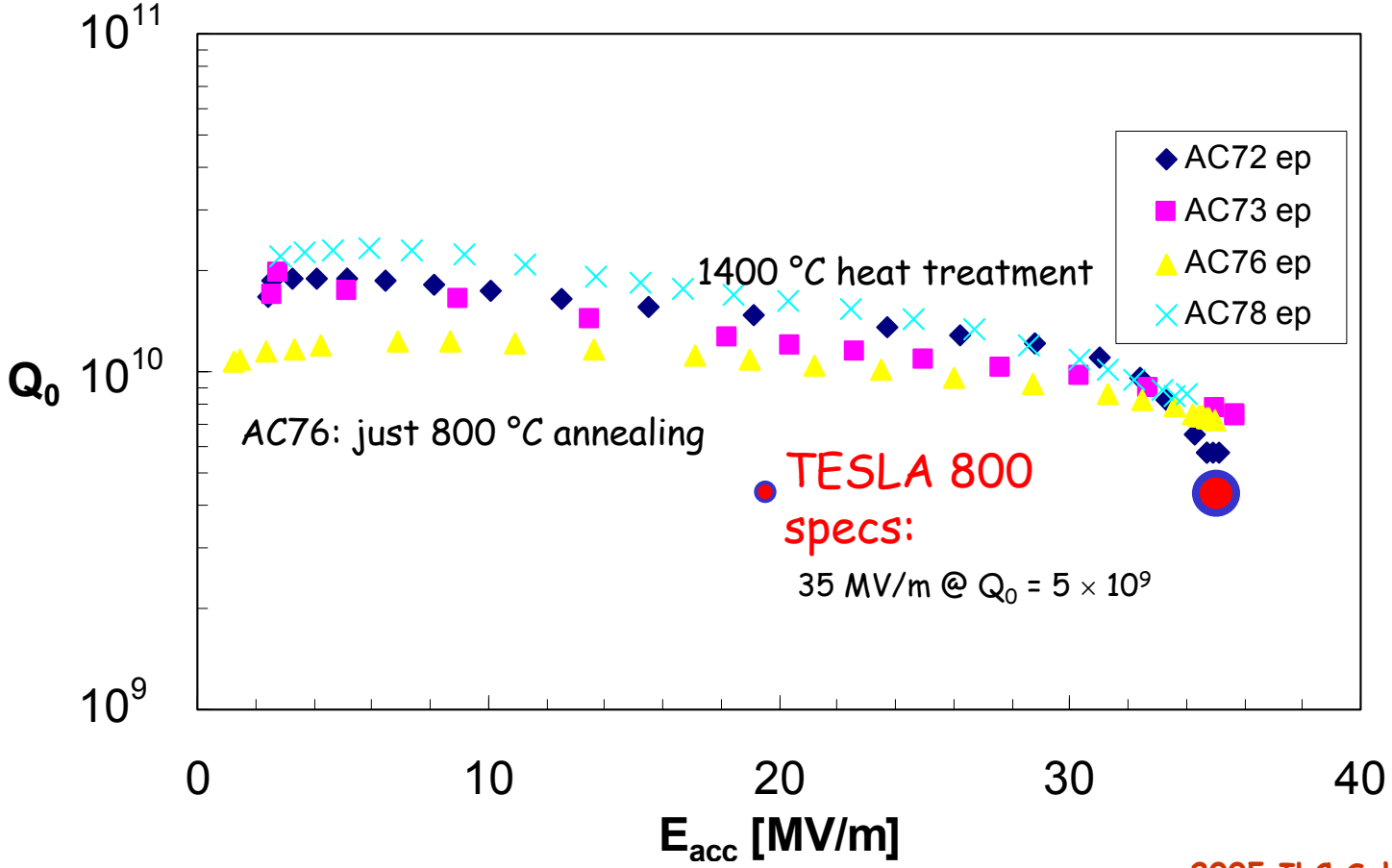
Electro-polishing (EP) instead of the Buffered Chemical Polishing (BCP)

- Much smuther surface, less local field enhancement
- Cleaning by High Pressure Rinsing more effective
  - Field Emission onset at higher field

TESLA-800 Performances with EP

First outstanding results from Vertical Test

- nine-cell cavities from the 3rd production
- EP at Nomura Plating by KEK



AC73: Full System long term test
in 1/8th Cryomodule (CHECHIA)

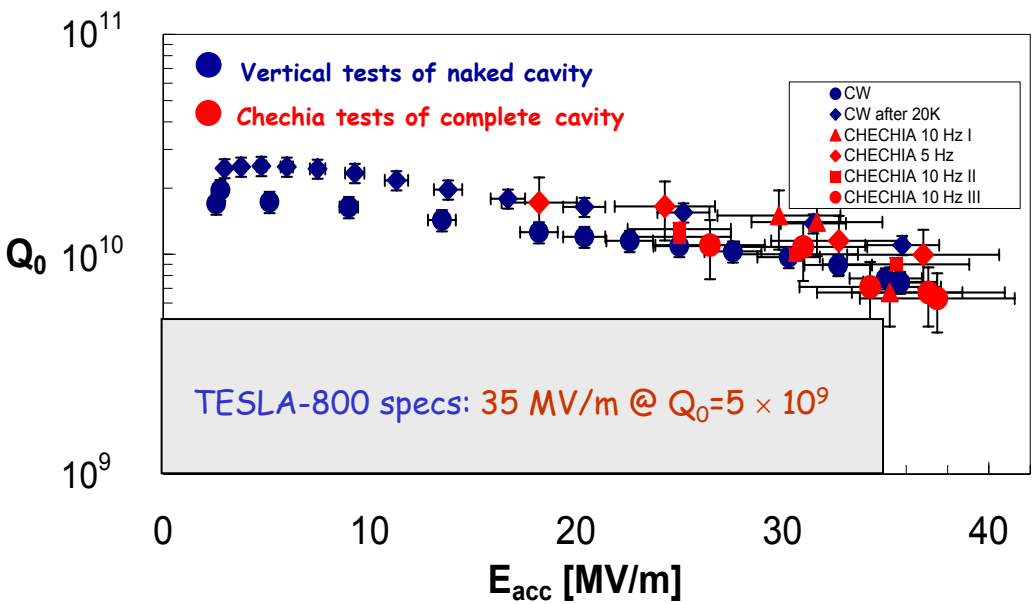
1100 hr continuous operation at 35MV/m

No 'faults' observed

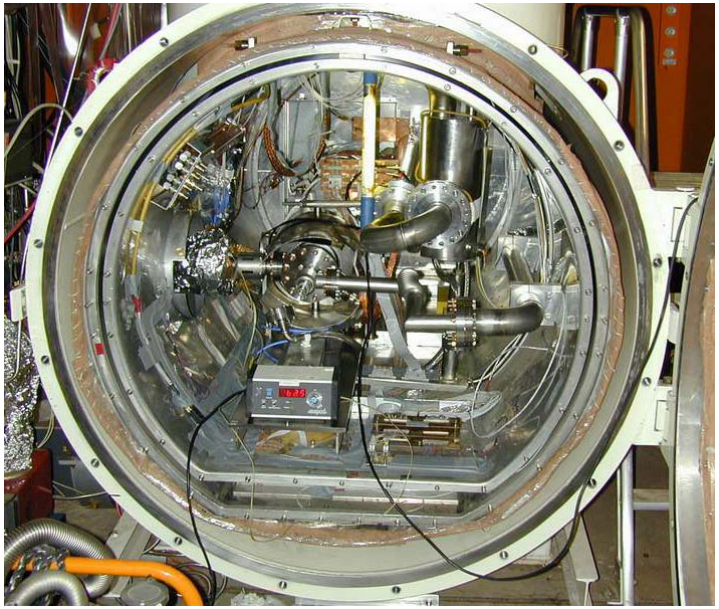
- due to couplers
- nor due to cavities

Forced 'trips' caused no damage to cavity/coupler

- No degradation observed
- Some improvement due to natural processing



The Horizontal Cryomodule "CHECHIA"



- Cavity is fully assembled
- It includes all the ancillaries:
  - Power Coupler
  - Helium vessel
  - Tuner (…and piezo)
- RF Power is fed by a Klystron through the main coupler
- Pulse RF operation using the same pulse shape as TESLA/TTF

The 35MV/m Cryomodule Test

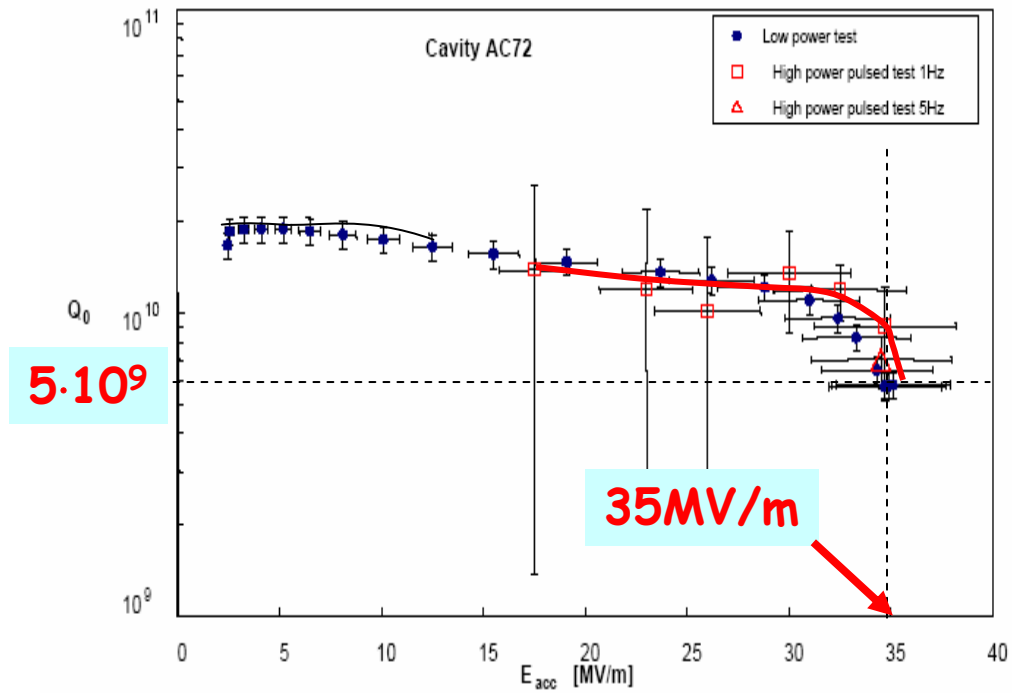
AC72: one of **five** high-performance EP cavities

Acceptance test in vertical cryostat

Transferred to

Full 1/8th CM horizontal test (CHECHIA)

- **HP coupler**
- **Tuner (fast/slow)**
- **full power (system) test**



The 35MV/m Cryomodule Test

AC72: one of **five** high-performance EP cavities

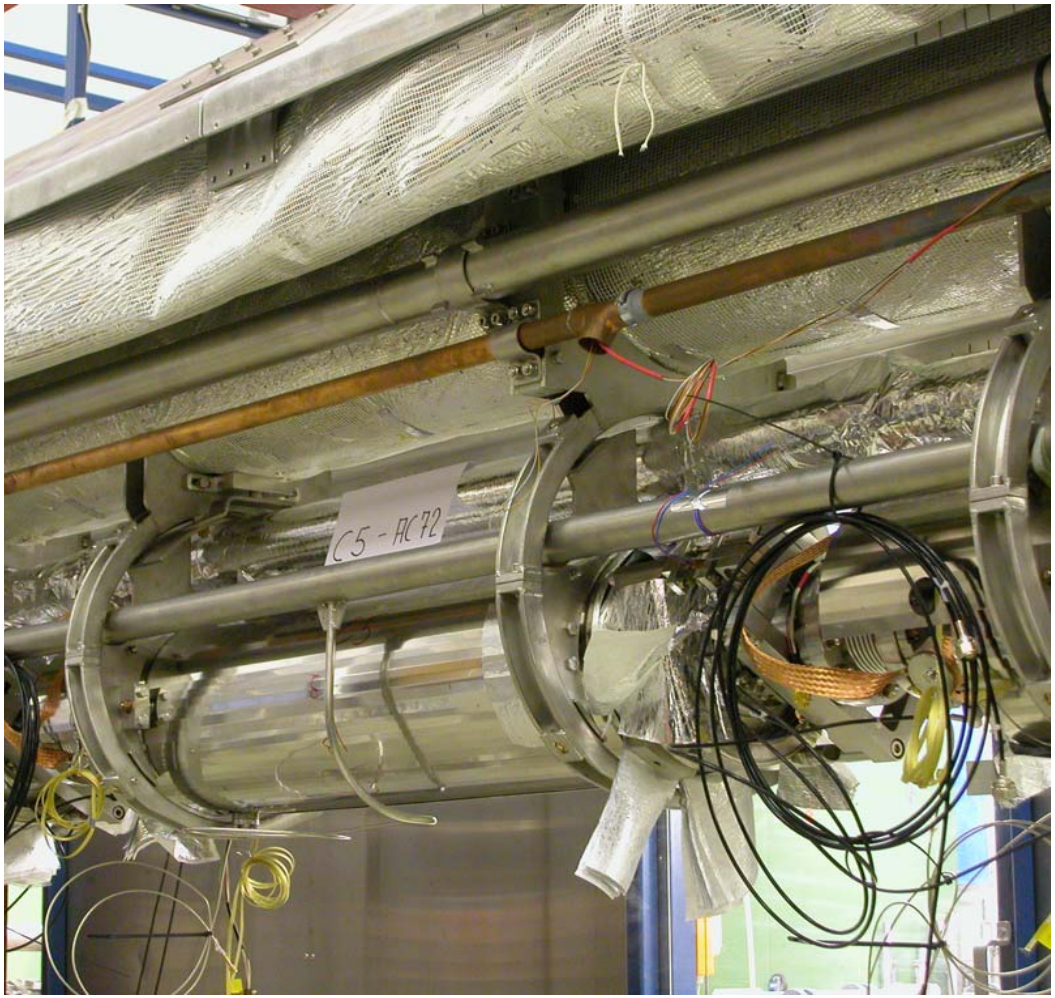
Acceptance test in vertical cryostat

↓ Transferred to

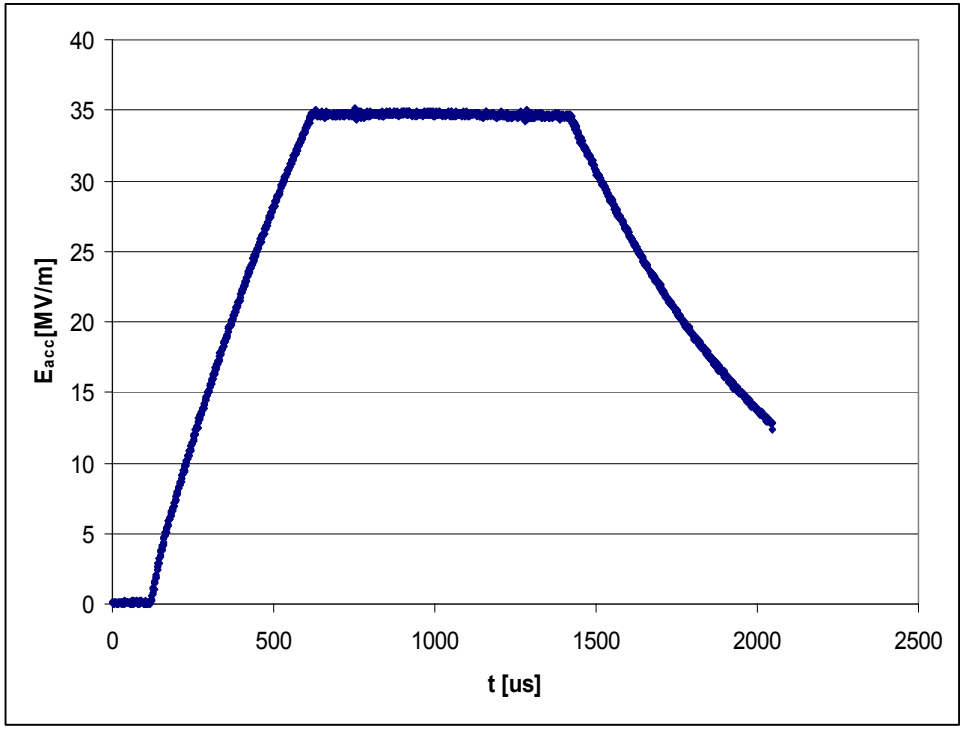
Full 1/8th CM horizontal test (CHECHIA)

↓ Transferred to

Full 8 cavity Cryomodule



The 35MV/m Cryomodule Test



RF pulse with feedback in cavity 5 (AC72) during beam acceleration

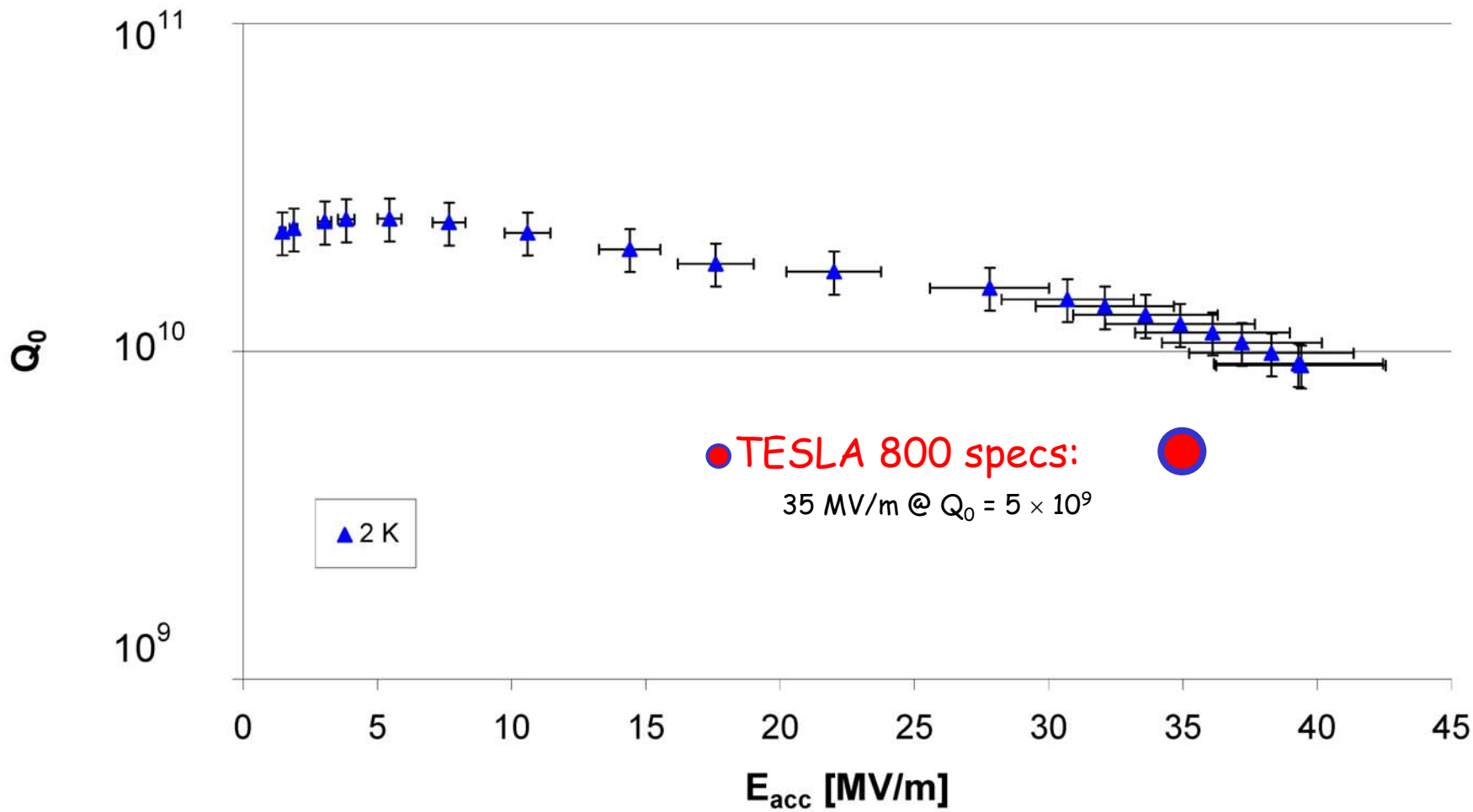
- RF measurements showed no degradation of performance (35MV/m achieved)
- RF gradient measurement calibrated using beam (energy spectrometer)
- No measurable radiation detected (no dark current)

No time for long-term system test due to TTF-II commissioning, but…

35 MV/m EP TESLA Cavity accelerates beam for the first time

Results on AC70 - 1

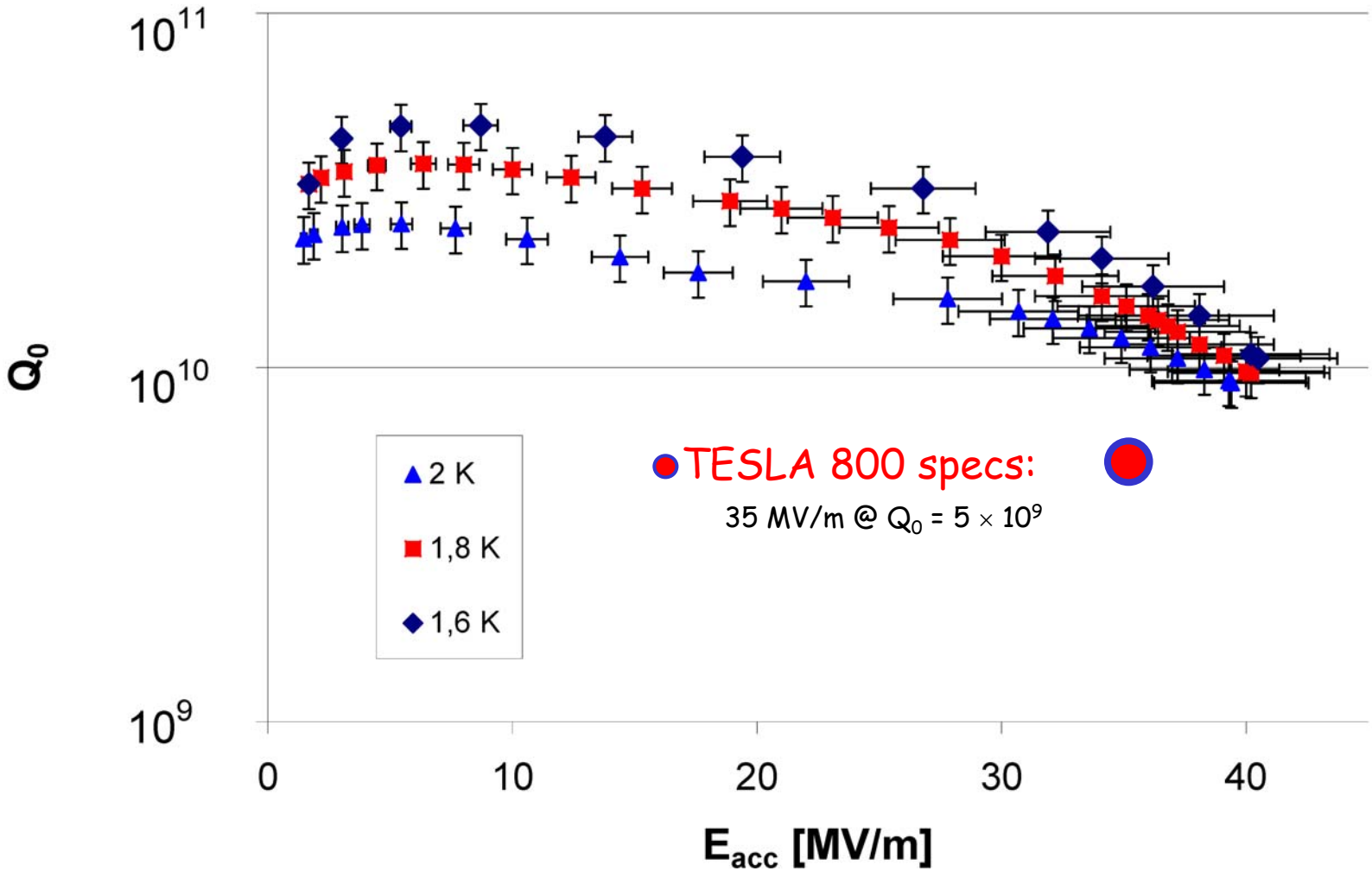
EP at the new DESY plan 800°C annealing 120°C Backing



Results on AC70 - 2

Very low residual resistance

Negligible Field Emission

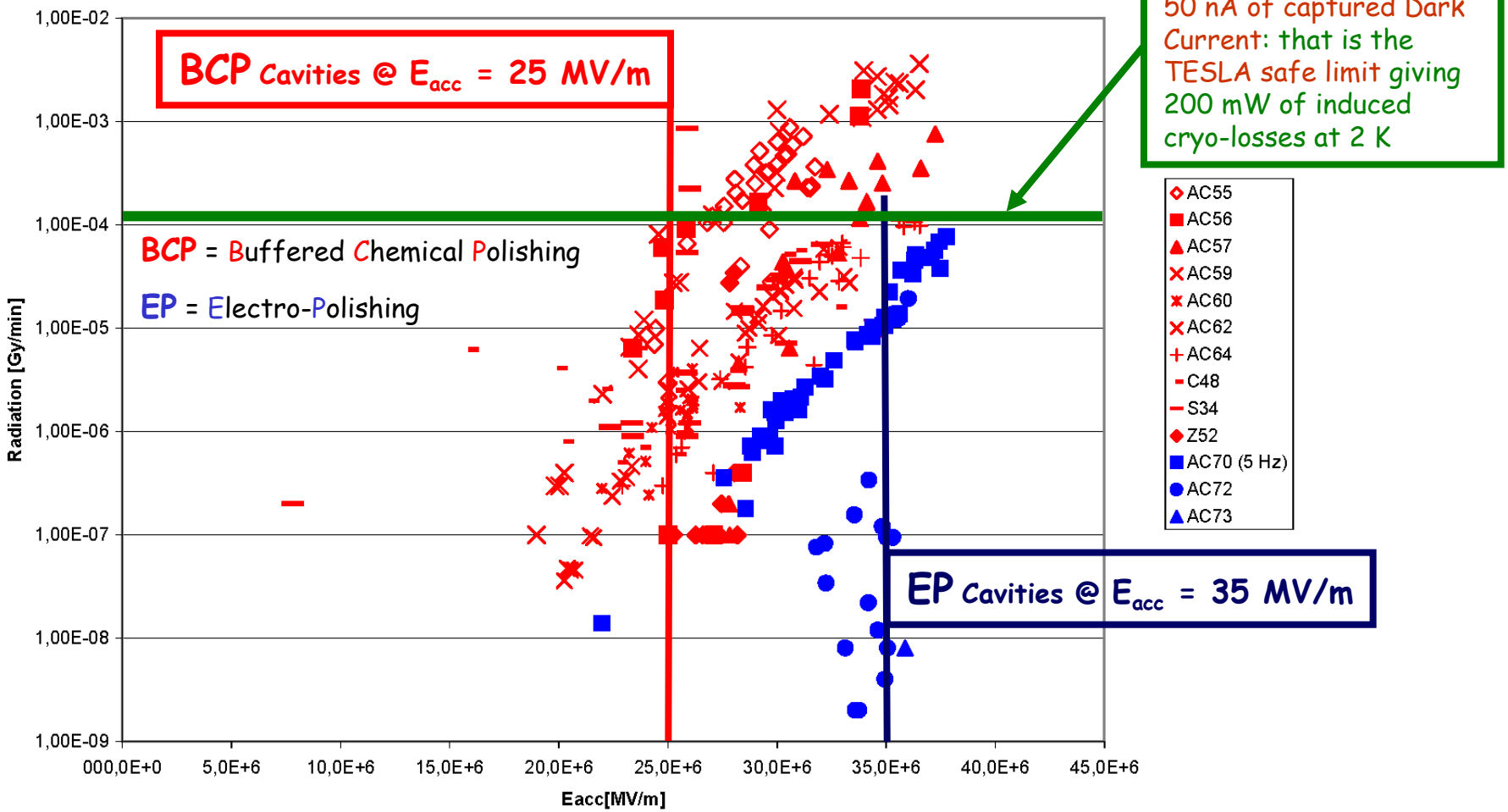


Field Emission pushed to very high field

BCP Cavities used in Modules 4 & 5 are in red, EP cavities in blue

Radiation Dose from the fully equipped cavities while High Power Tested in "Chechia"

"Chechia" is the horizontal cryostat equivalent to 1/8 of a TTF Module

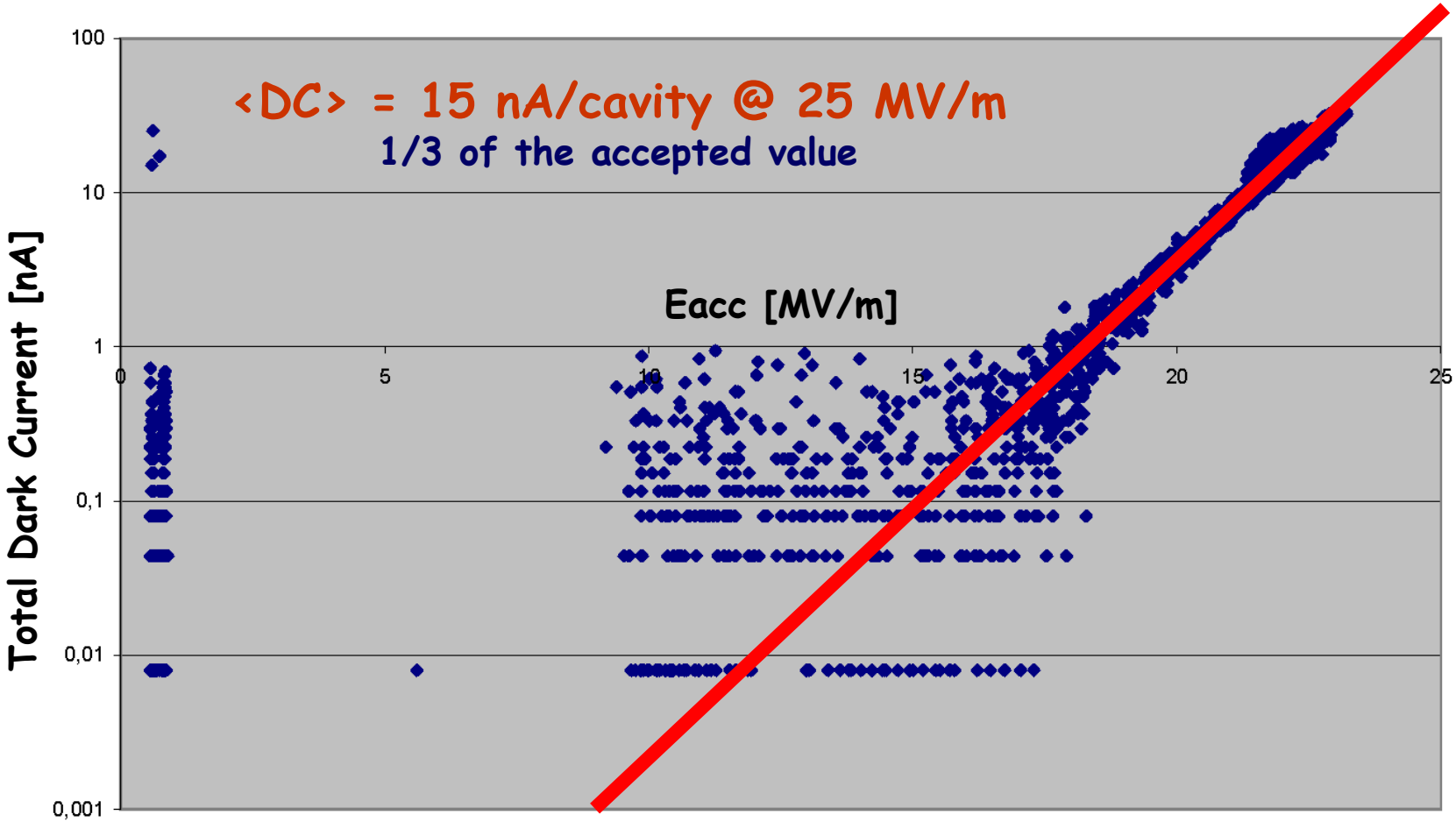


Dark Current Measured on ACC4

During coupler conditioning, August 23, 2003.

Total Dark Current generated by all the 8 cavities (BCP) of module ACC4

Dark Current well below the limit (400 nA) without cavity processing

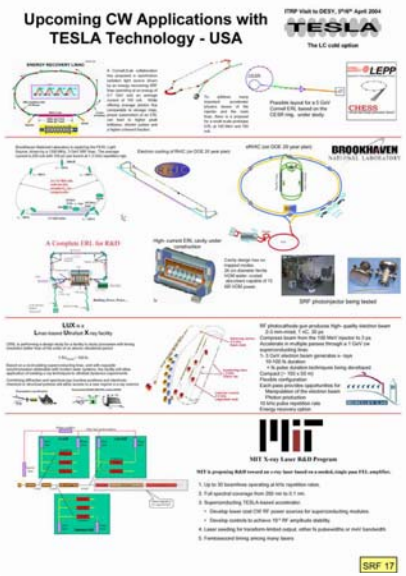


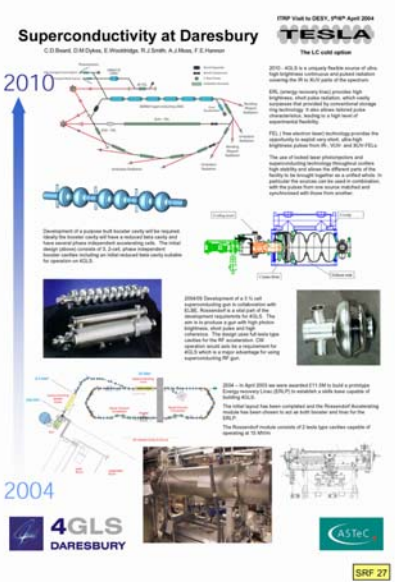
SRF Technology Beyond ILC

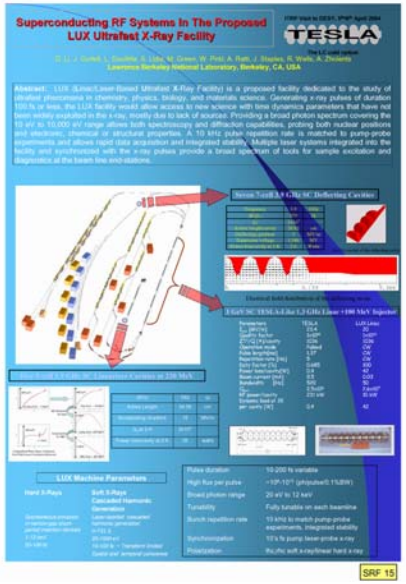
- Most of the new accelerator based projects, in construction or just proposed, are widely using Superconducting RF technology.
- The worldwide coordinated effort behind the TESLA project has been driving a new level of understanding of the past limiting factors.
- At present industry is producing turn-key reliable systems that include SRF cavities and cryo-ancillaries.
- The European X-FEL will represent the first large scale application based on the TESLA Technology. Its realization will be naturally synergic with the Linear Collider
- **The ITRP recommendation of using "cold technology" for ILC has been the right one.**

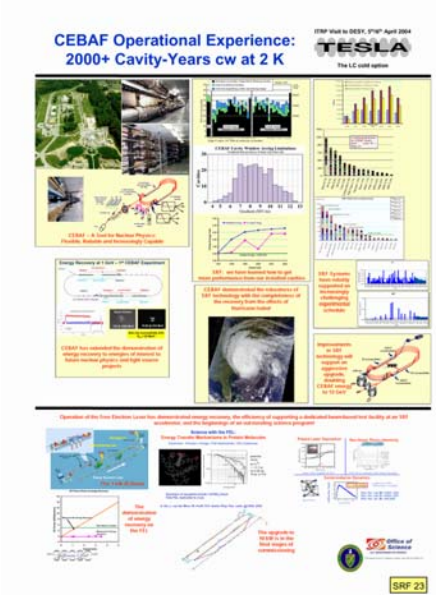
Projects and TESLA Technology

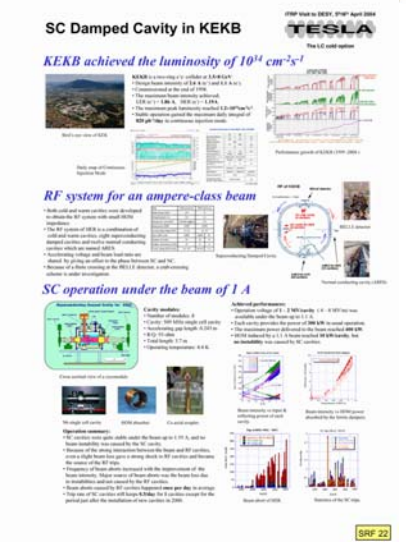
A Few Examples

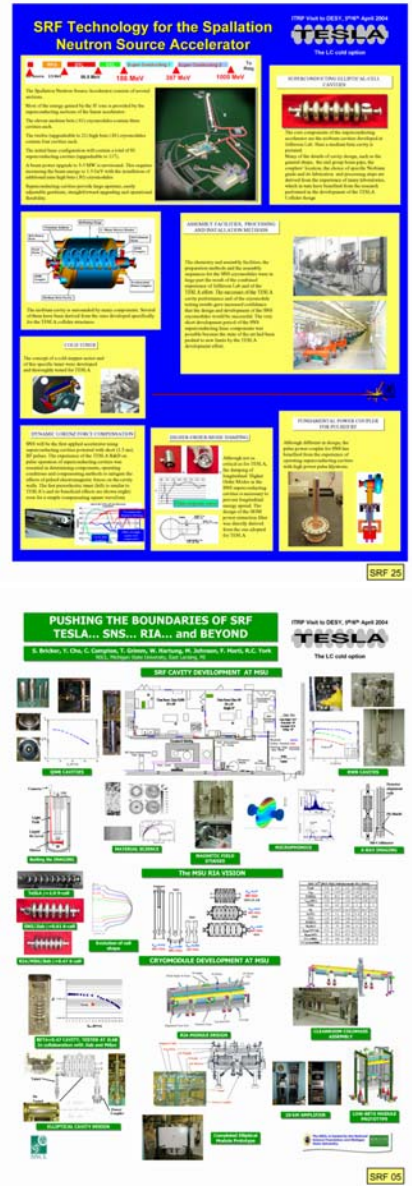
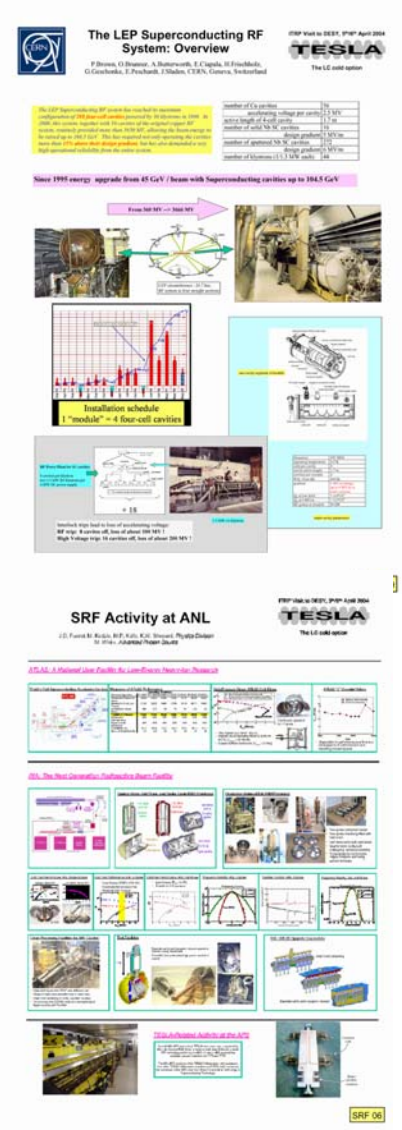










Distribution of TESLA Technology

A Few Examples