深圳综合粒子设施研究院

Institute of Advanced Science Facilities, Shenzhen

Cycle of Seminars by Carlo Pagani

Seminar # 2

SRF: from Origin to the TESLA Revolution

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UNIVERSITAS STUDIORUM MEDIOLANENSIS

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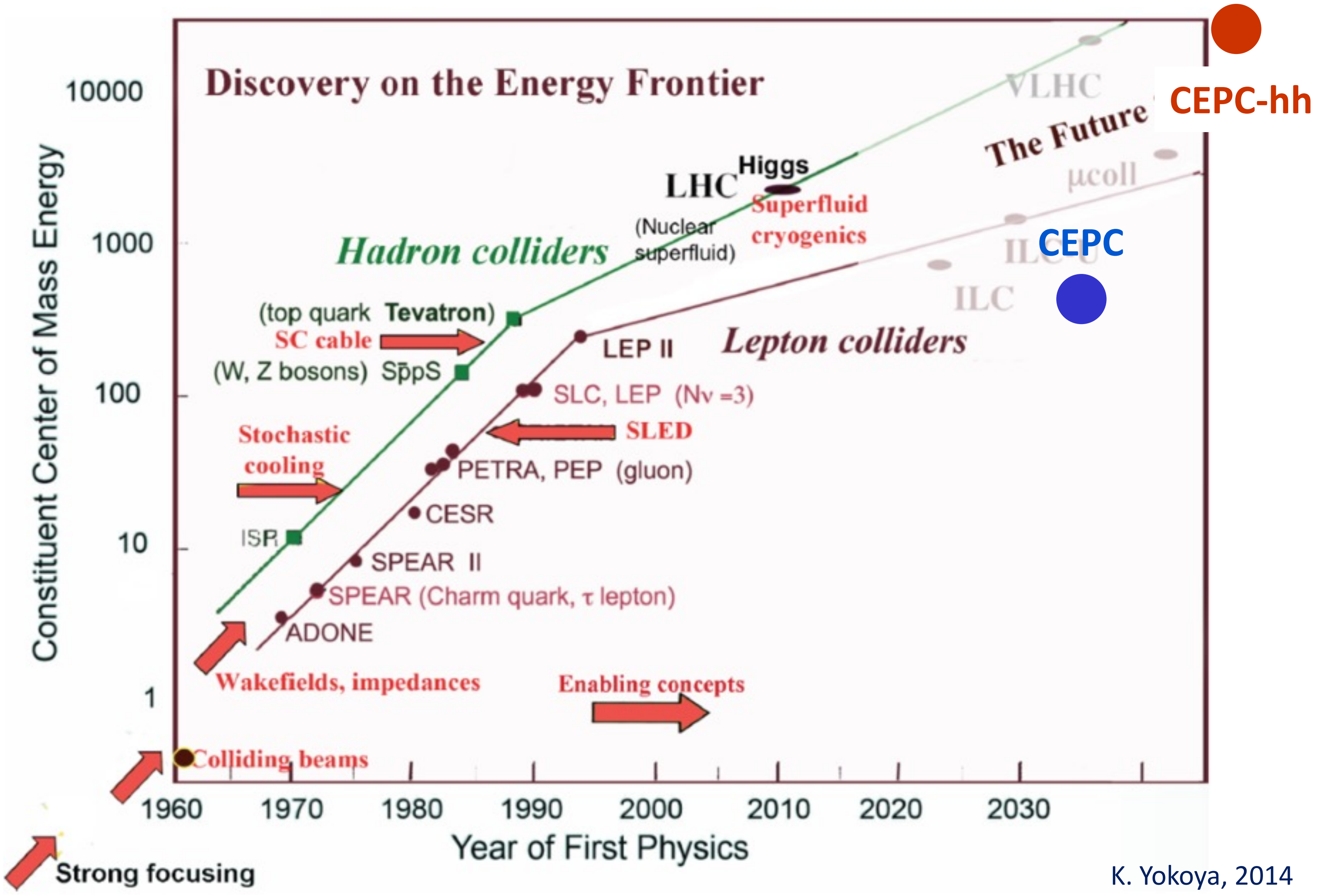
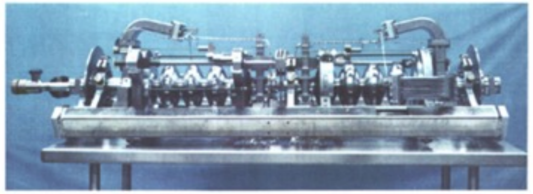
Livingston chart for Colliders

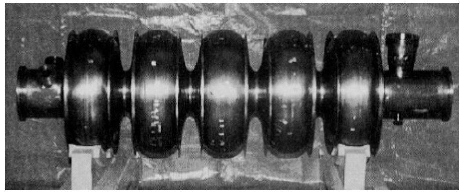


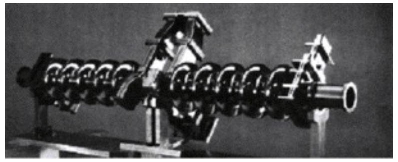
K. Yokoya, 2014

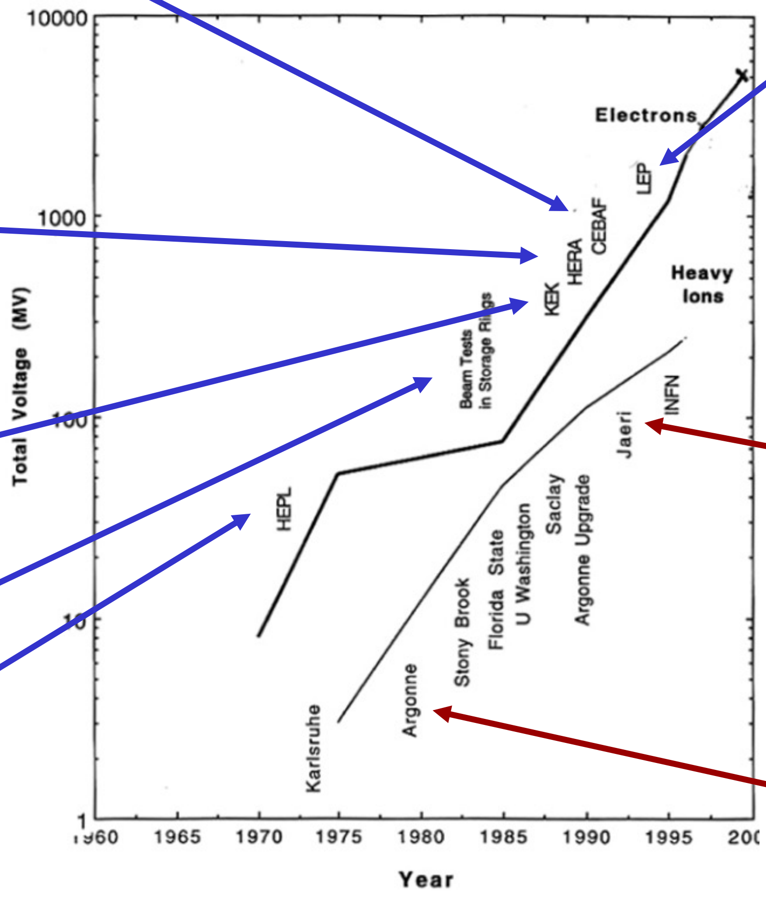
SCRF From HEPL to year 2000

"Livingston Plot" **from Hasan Padamsee**









Energy gain and dissipated power

To transfer energy efficiently to particles, very high electric field is required

$$\Delta E_{particle} = \int \vec{F}_{Lorentz} \cdot d\vec{s} = q \int \vec{E} \cdot \vec{v}\, dt$$

In any structure (cavity) holding an electromagnetic field, both dissipated power and stored energy scale quadratically with the fields

The efficiency of a cavity depends on:

Its quality factor, Q

driven by the surface resistance, R_s

$$Q = \frac{\omega U}{P_{diss}}$$

U is the energy stored in the cavity

P_{diss} is the power dissipated on its surface

Its shunt impedance, r

function of the cavity geometry and of the surface resistance, R_s

$$r = \frac{(\Delta V)^2}{P_{diss}}$$

ΔV is the voltage seen by the beam

$$\frac{r}{Q} = \frac{(\Delta V)^2}{\omega U}$$

"r over Q" is purely a geometrical factor

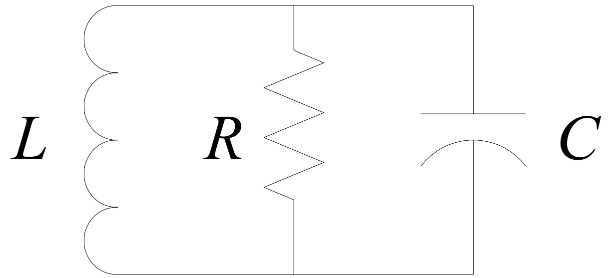
For efficient acceleration Q, r and r/Q must all be as high as possible

→ Good material for maximum Q and r (that is minimum P_{diss})

Good design for maximum r/Q

Cavity lumped circuit model and R_s

A cavity at the fundamental mode has an equivalent resonant lumped circuit



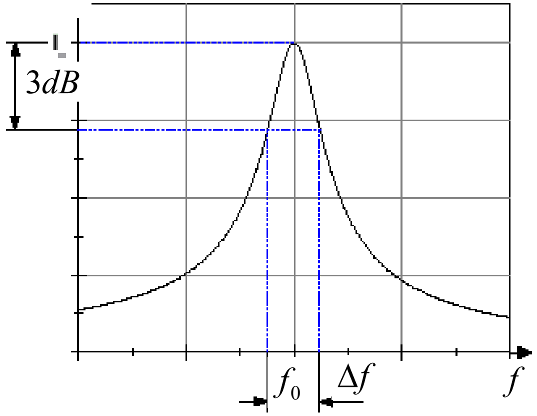
$$\omega_0 = \frac{1}{\sqrt{LC}} \qquad Q = \omega_0 RC$$

$$\omega_0 = 2\pi f_0$$

$$P_{diss} = \frac{V^2}{2R}$$

Q determines the frequency band Δf

$$\Delta f = \frac{f_0}{Q}$$



R proportional to Q determines P_{diss}

$$R \propto Q$$

R depends inversely on the cavity R_s through a geometrical factor

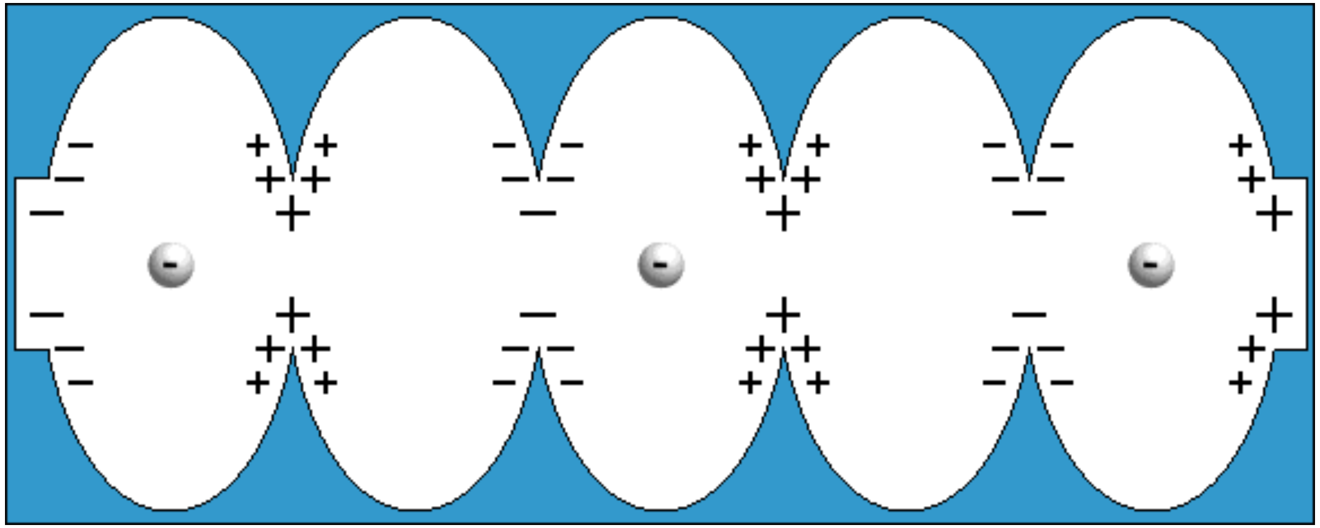
$$R \propto \frac{1}{R_s}$$

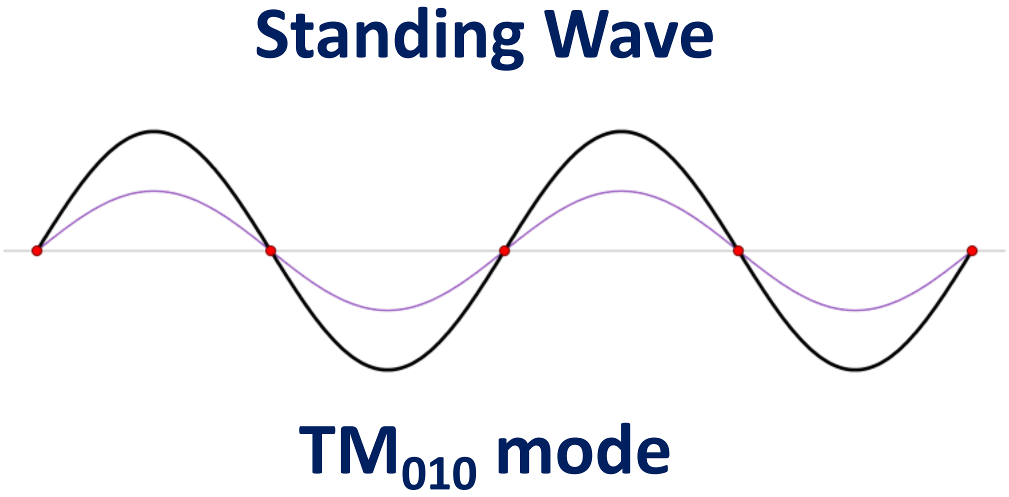
In practice, for a given geometry and a given accelerating field the surface resistance R_s **plays the crucial role of determining** the dissipated power, that is **the power required to sustain the field**

$$R_s$$

Acceleration via RF Cavity

- **An accelerating space**, usually called **radio-frequency (RF) cavity**, **is nothing but a container crossed by the beam in which is stored a non conservative electric field** (rotational) that, when the bunch of particles is passing through, is found to be properly orientated in the desired direction.





RF to transfer Energy to the Beam

In the accelerator the world RF takes care of all the variety of items that are required to accomplish this task of creating a region filled of electromagnetic energy that can be sucked by the beam while crossing it.

An "**RF power source**" is used to fill, via a "**coupler**", the "**RF cavity**", or resonator that is the e.m. energy container from which the beam is taking its energy.

What we ask to a good cavity?

High Q for low losses

$$Q = \omega \frac{U}{P_{diss}}$$

U = stored energy

P_{diss} = dissipated power

Small R_s for high Q

$$Q = \frac{G}{R_s}$$

R_s = surface resistance

G = cavity geometrical factor

Superconductivity whenever possible

For a good but not perfect conductor ($\rho \neq 0$), the fields and currents penetrate into the conductor in a small layer at the cavity surface (the skin depth, δ)

With RF fields, a SC cavity dissipate power, not all electrons are in Cooper pairs.

$$R_s = \frac{\rho}{\delta} \neq 0$$

$$P_{diss} = \frac{R_s}{2}\int_S H^2 dS$$

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

Cu: $R_s[\mathrm{m}\Omega] = 7.8 f^{\frac{1}{2}}[\mathrm{GHz}]$

SC SuperConducting

NC or RT NormalConducting

In NC linac a huge amount of power is deposited in the copper structure: MW to have MV

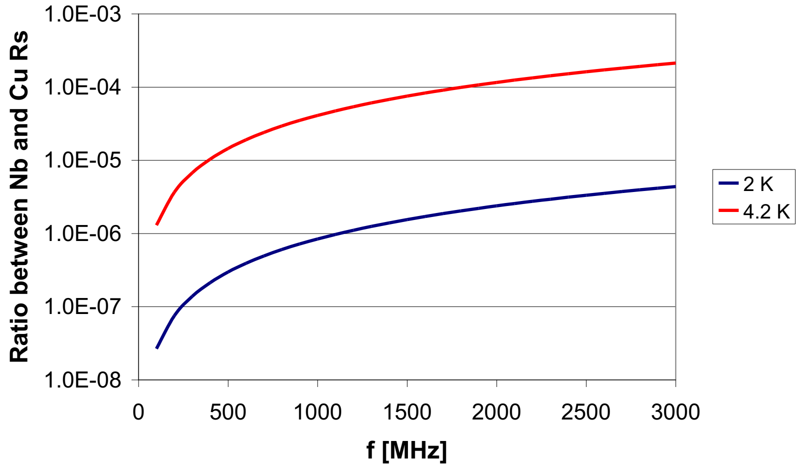
Pulsed operation and Low Duty Cycle

Superconductivity, drastically reduces the dissipated power. But some drawbacks

- Higher complexity: refrigeration and cryomodules
- Higher technology: cavity treatments
- Carnot and refrigeration plant efficiencies
- Simpler geometries: lower shunt impedance

And two big advantages:

- Large bore radius: less beam losses
- CW or high duty cicle preferred



$$\eta_C = \frac{T_2}{T_1 - T_2} = \begin{cases} 1/70 \text{ for } T_1 = 300\mathrm{K}, T_2 = 4.2\mathrm{K} \\ 1/150 \text{ for } T_1 = 300\mathrm{K}, T_2 = 2\mathrm{K} \end{cases}$$

$$\eta_{th} = \begin{cases} 25-30\% \text{ at } T = 4.2\mathrm{K} \\ 15-20\% \text{ at } T = 2\mathrm{K} \end{cases}$$

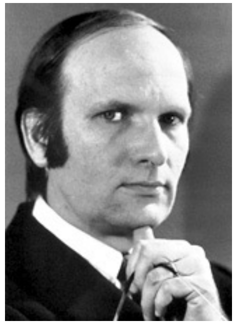
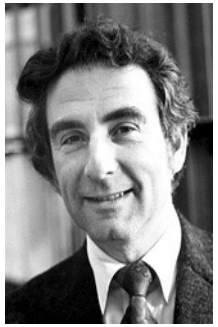
$$\eta_{tot} = \eta_C \eta_{th} \approx \begin{cases} 250\mathrm{W} \text{ at } 300\mathrm{K} \text{ for } 1\mathrm{W} \text{ at } T = 4.2\mathrm{K} \\ 800\mathrm{W} \text{ at } 300\mathrm{K} \text{ for } 1\mathrm{W} \text{ at } T = 2\mathrm{K} \end{cases}$$

Superconductivity as soon as possible

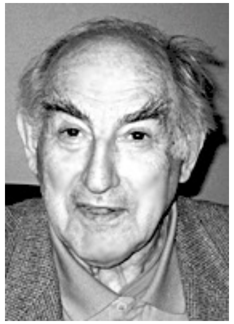
- **Whatever geometry the cavity has**, the **power dissipated by Joule effect is proportional to its surface resistance and to the square of the field inside it.**
- **At first, it was not clear that superconductivity had much value for RF technology**. When a superconductor is exposed to a time-varying electromagnetic field, **the electrons that are not coupled as Cooper pairs lead to energy dissipation** in the shallow layer of the superconductor surface in which the electric and magnetic fields are dancing together to sustain the rotational electric field that transfer the energy to the beam.
- **But it was soon realized that** in the practical frequency range of RF accelerators, **from a few hundred MHz to a few GHz,** the use of SRF cavities would produce in any case a significant gain. **It was simply a question of developing the technology**, and **that required investment and big projects**.

Superconductivity: Historical Overview

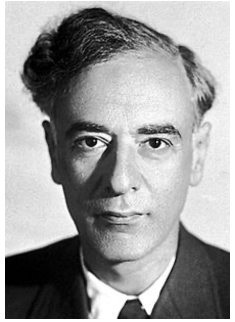
- 1908 Liquefaction of helium (4.2 K)
- 1911 Zero resistance
- 1933 **Meissner** effect
- 1935 Phenomenological theory of H. & F. **London**
- 1950 **Ginzburg** – **Landau** theory
- 1951 – 2 types of superconductors (**Abrikosov**)
- 1957 **Bardeen** – **Cooper** – **Schrieffer** microscopic theory
- 1960 Magnetic flux quantisation
- 1962 Josephson effect
- 1986 High temperature superconductors (**Bednorz** – **Müller**)


Bardeen – Cooper – Schrieffer (BCS)

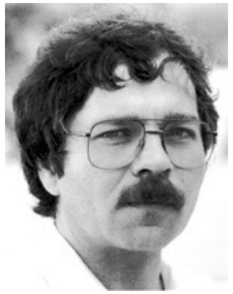


Ginzburg



Landau

Abrikosov



Bednorz

Müller

Surface resistances in NC and SC Cavities

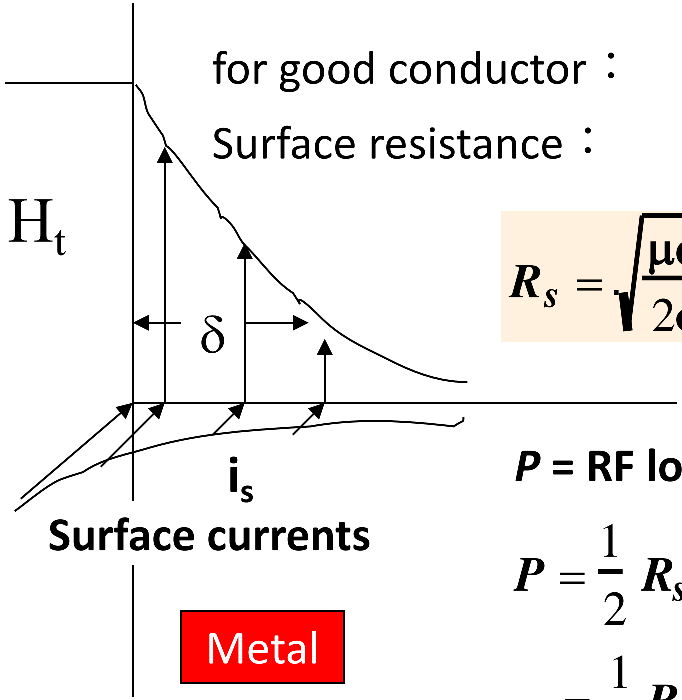
Normal conducting

δ = skin depth of microwave

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

Surface resistance：

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



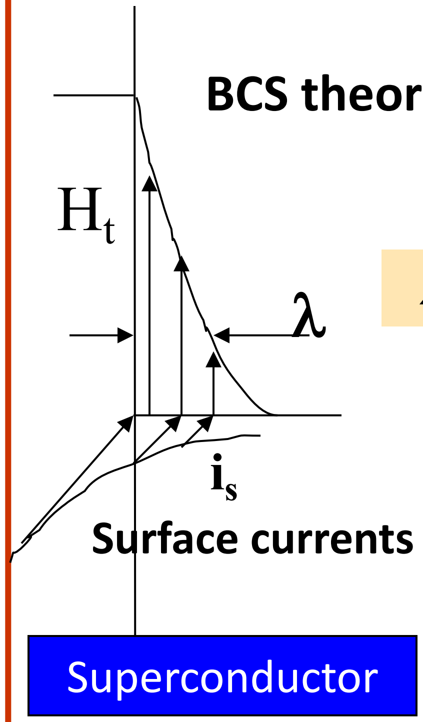
***P* = RF losses**

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

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

Superconducting

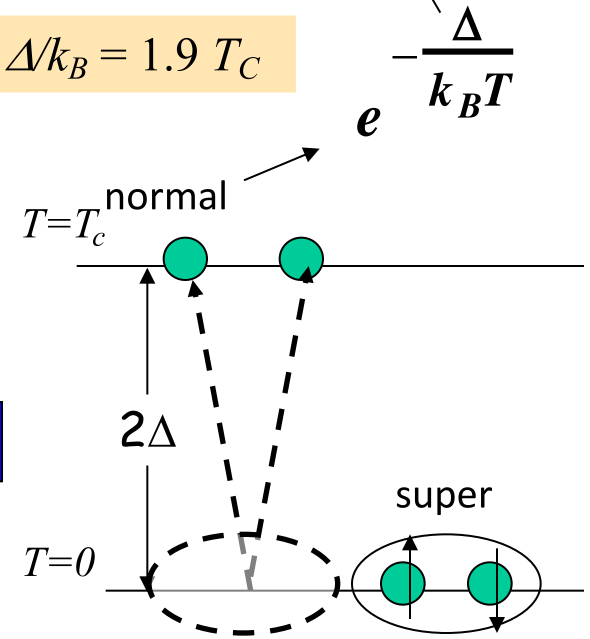
λ = London penetration depth



BCS theory

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

$$\Delta / k_B = 1.9\, T_C$$



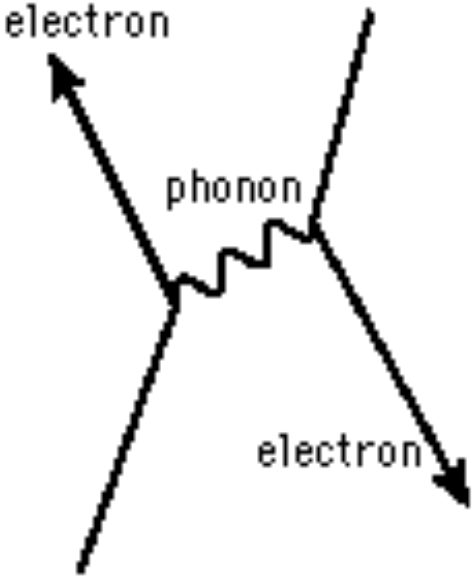
$$Q_0 = \omega U/P = G/R_s$$

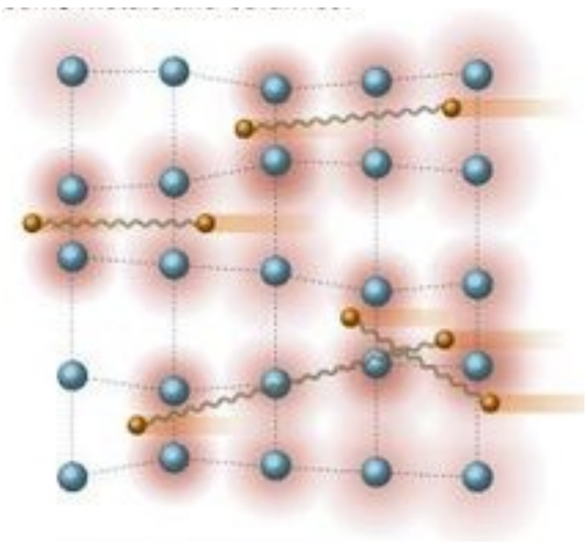
Cooper pairs and Zero Resistance

Pairing of electrons close to the Fermi level into Cooper pairs through interaction with the crystal lattice

- Boson (no Pauli exclusion principle)
- All Cooper pairs condense to the same ground state
- Coherent wave functions → no scattering → zero resistance

Size of a cooper pair is large compared to the lattice constant and is related to the coherence length ξ





Estimated size of a cooper pair:

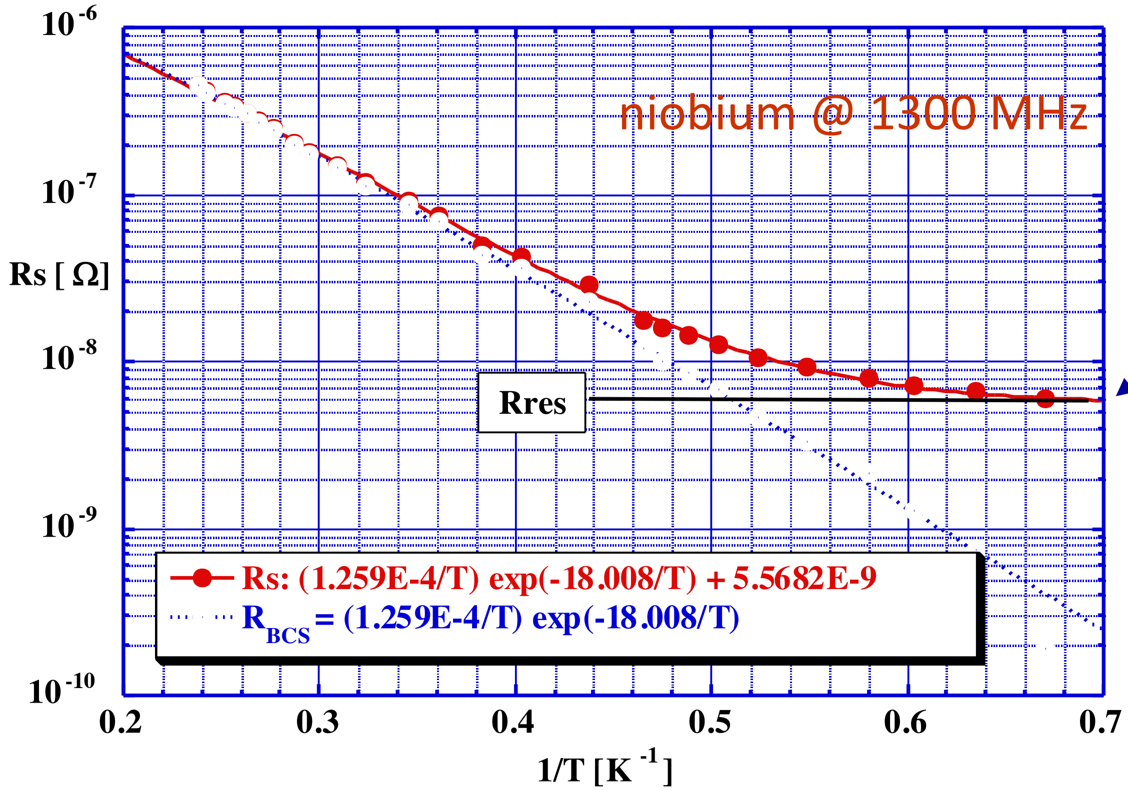
- Relaxation time of the lattice: $2\pi/\omega_D \approx 10^{-13}$s
- Electrons move with $v_F \approx 10^6$m/s
- Distance between electrons forming a cooper pair:

$$\xi \approx (2\pi/\omega_D)\, v_F \approx 10^{-7}\text{m}$$

The Real Surface Resistance

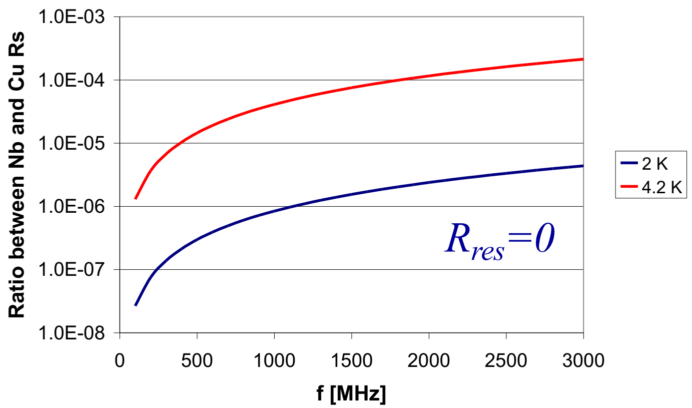
$$R_s = R_{BCS} + R_{res}$$

$$R_{BCS}[\mathrm{n}\Omega] = 9\times10^4 \frac{f^2[\mathrm{GHz}]}{T[\mathrm{K}]}\exp\left(-\frac{17.6}{T[\mathrm{K}]}\right)$$



R_{res}

due to surface defects, contamination, trapped magnetic field and other



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 → 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 partially understood

Effect of surface oxides (hydrides), trapped flux, defects and more fundamental mechanisms

$R_{res} \approx$ 1-20 nΩ

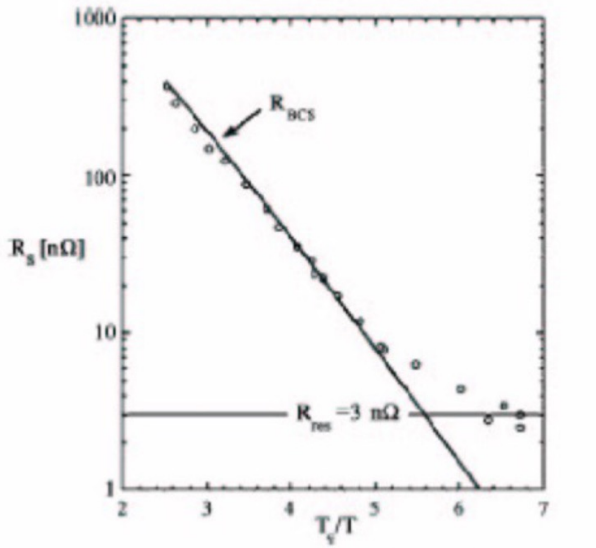
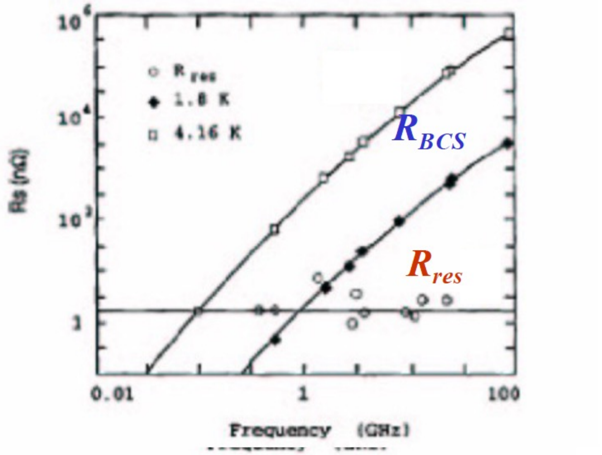


Figure 16. Measured temperature dependence of the surface resistance of a Nb cavity at 1.3 GHz. In this semi-log plot, the linear region gives an energy gap of $\Delta = 1.9kT_c$. The residual resistance is 3 nΩ.

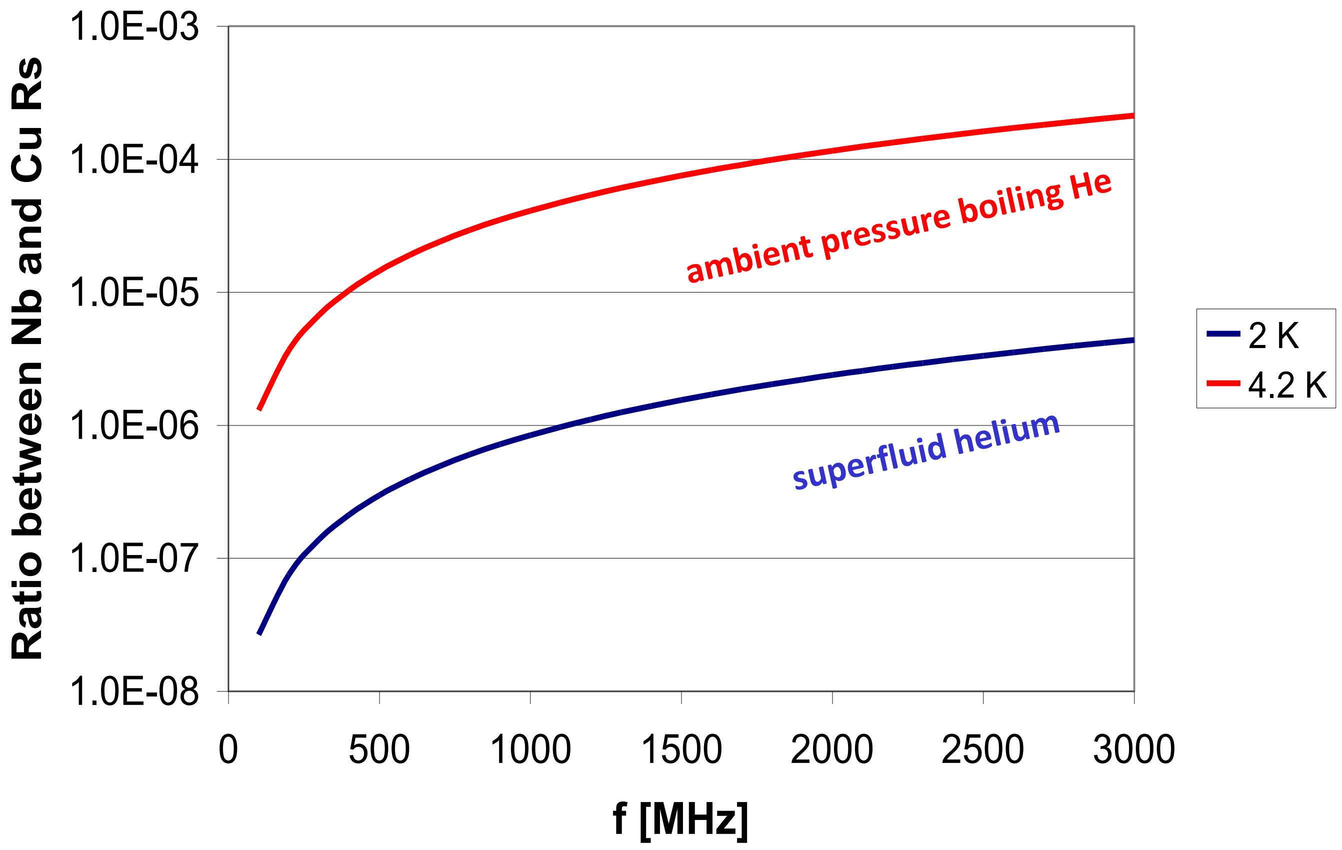


Superconducting RF vs NC-RF

Power dissipated on the cavity walls to sustain the field is:

$$P_{diss} = \frac{R_s}{2}\int_S H^2 dS$$

Good, but the gain of up to 6 order of magnitudes is not guaranted and it's not for free



What we need to use SRF

- The power is deposited at the operating temperature of few K
- We need to guarantee and preserve the 2 K environment
- Cavity is sensitive to pressure variations; only viable environment is sub-atmospheric vapor saturated He II bath
- We need a thermal “machine” that performs work at room temperature to extract the heat deposited at cold
- The Thermal machine efficiency is just a fraction of the Carnot efficiency
- Less favorable Geometrical Factor G

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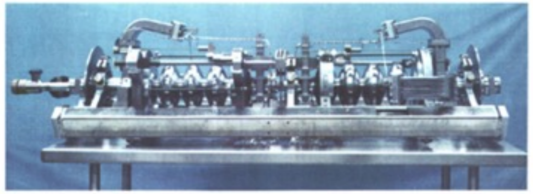
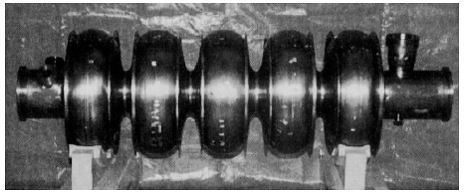
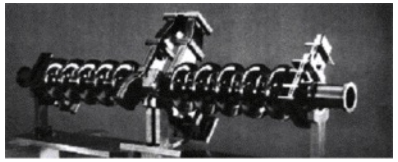
From pioneering age to first real success

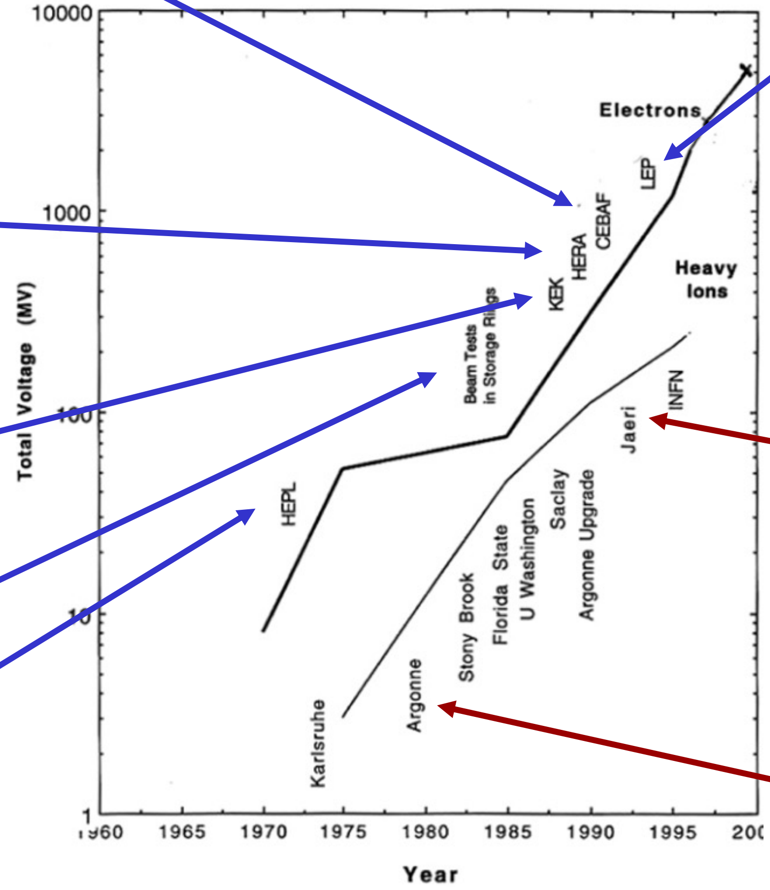
- The High-Energy Physics Lab **at Stanford University** was a pioneer in applying SRF to accelerators, demonstrating the **first acceleration of electrons with a lead-plated single- cell resonator in 1965**.
- Also **in Europe**, in the late 1960s, SRF was considered for the design of proton and ion linacs at **KFK in Karlsruhe**. In order to be superior to the competing technology of normal-conducting RF, a moderate field of few MV/m was necessary. **By the early 1970s SRF has been introduced in the design of particle accelerators, but results were still modest** and a number of limiting factors had to be understood.
- **The first successful test of a complete SRF cavity at high gradient and with beam was performed at Cornell's CESR facility at the end of 1984**, involving **a pair of 1.5 GHz, five-cell bulk niobium cavities with a gradient of 4.5 MV/m**. This cavity design was then used as **the basis for the CEBAF** facility at Jefferson Lab.

From HEPL to year 2000

“Livingston Plot” **from Hasan Padamsee**





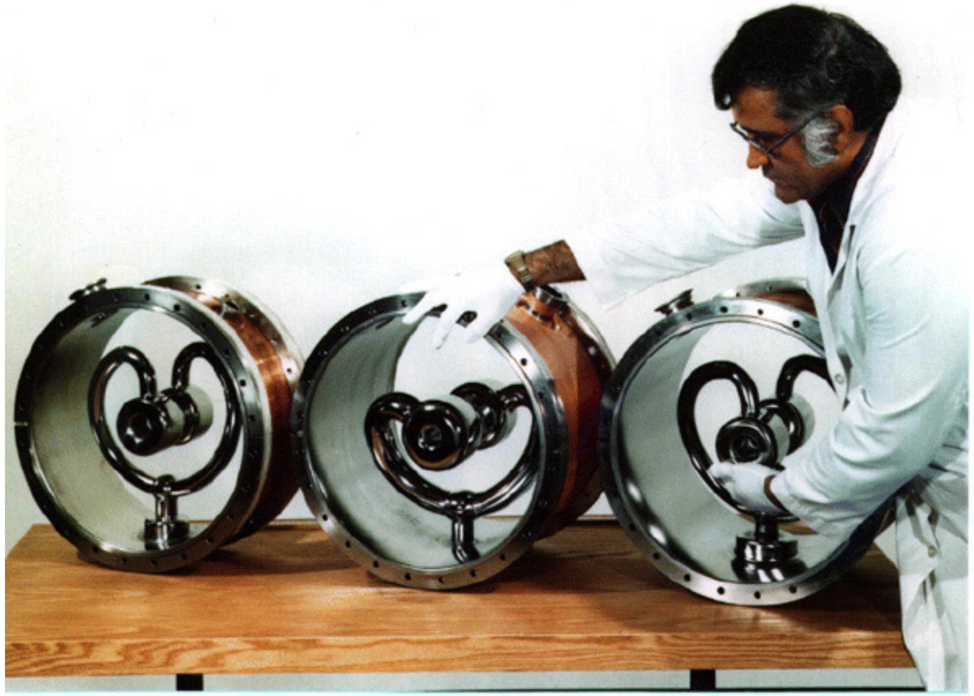


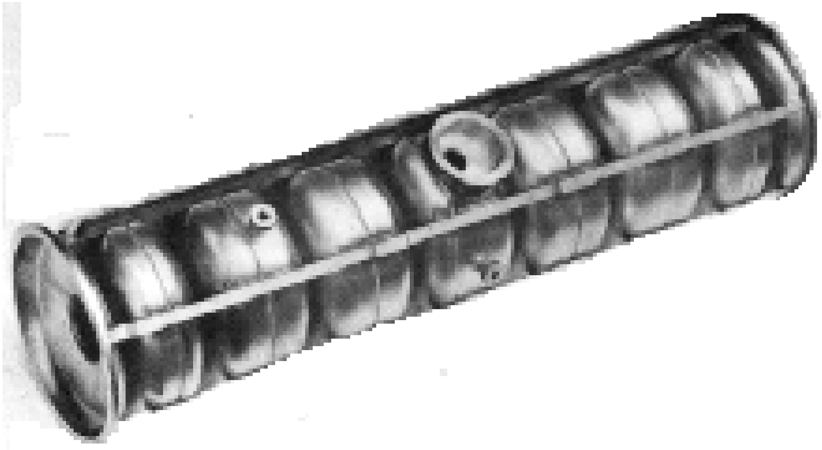
From the pioneering age to 1984

Argonne National Labs

ATLAS: Heavy-ion Linac

- Originated at Caltech
- Implementd and used in other labs for β ~ 0.1





Stanford University

HEPL: Electron Linac for FEL

- First multicell electron cavity: $\beta = 1$

Limiting Problems

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

Cavity treatments and cleanness

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

Microphonics

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

Multipactoring

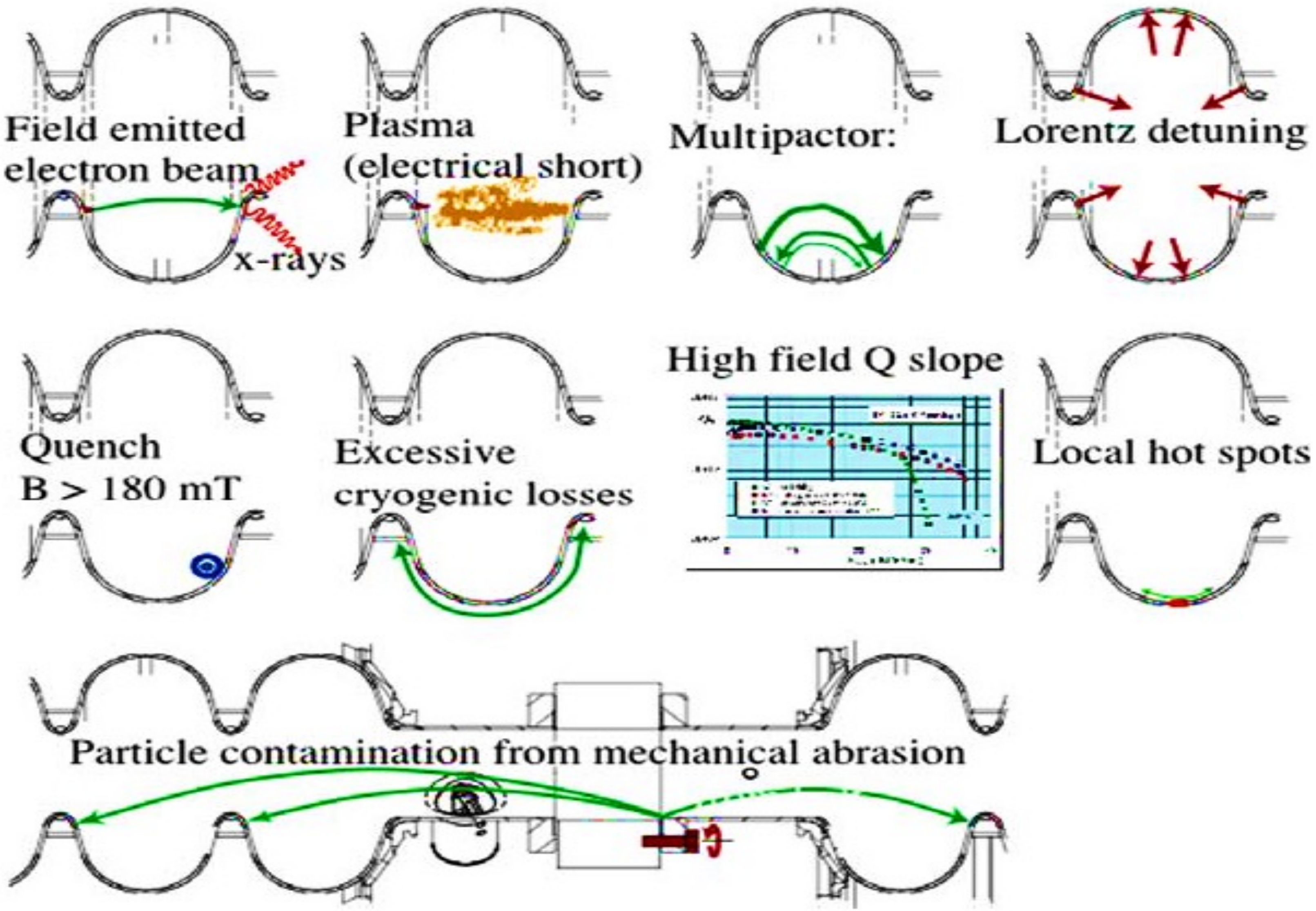
- MP has been the major limit for HEPL, and electron linacs to 1984
- Pill-box like geometry: higher shunt impedance but higher MP problems

Quenches/Thermal breakdown → low RRR and NC inclusions

Field Emission

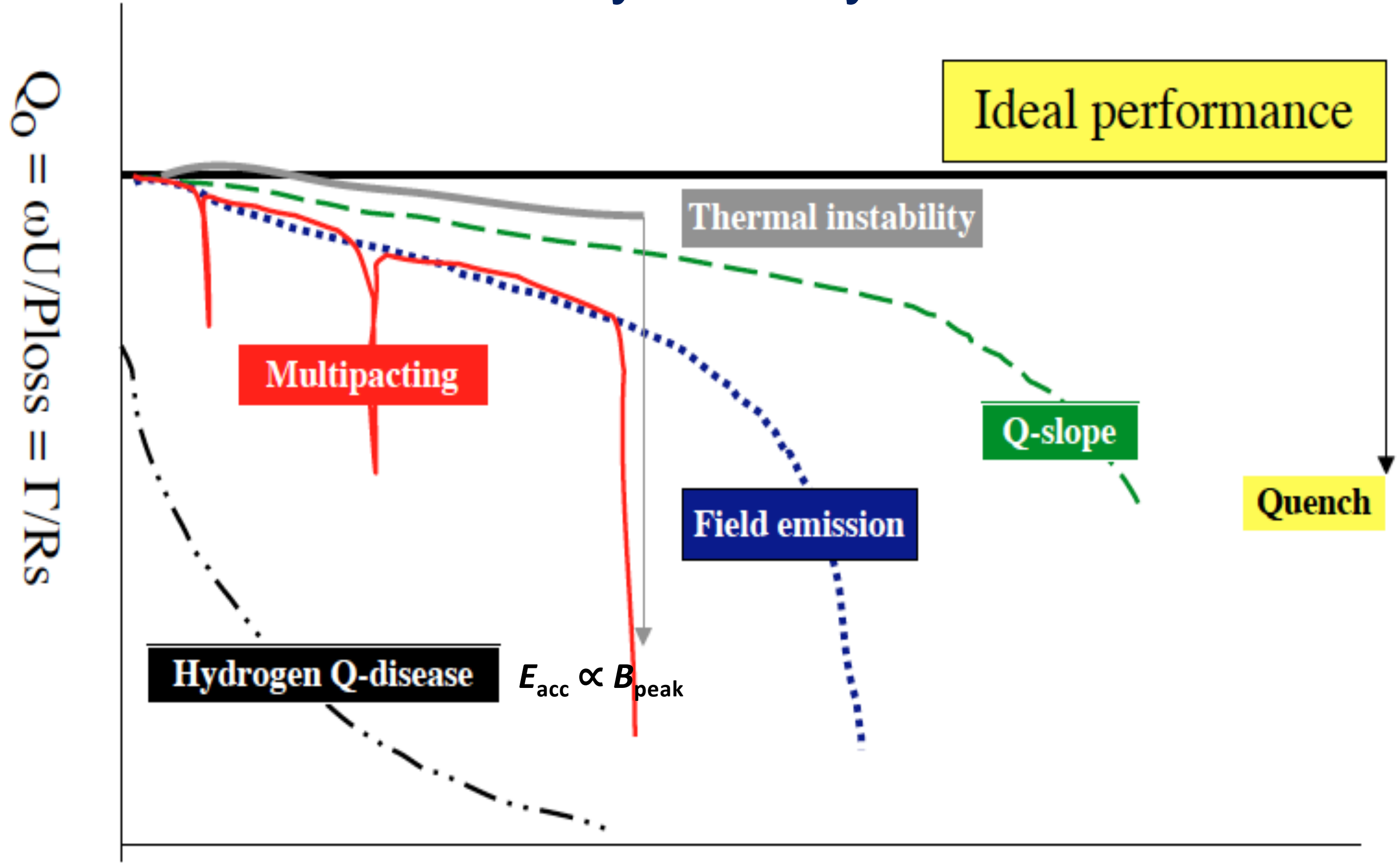
- General limit at those time because of poor cleaning procedures and material

SC cavities may have various "illness"



Performance Limitations of SRF cavities

There are two parameters which define the performance of an SRF cavity: Quality factor and the accelerating gradient

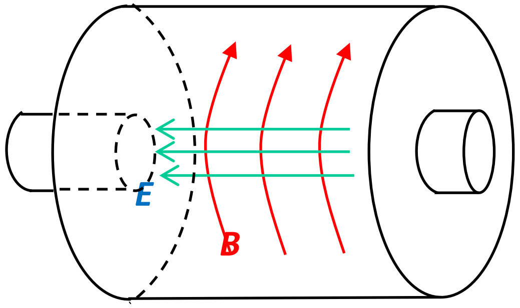


The quality factor. Remember:

$Q_0 = G/R_S = \omega U/P_{loss}$. G = geometry factor

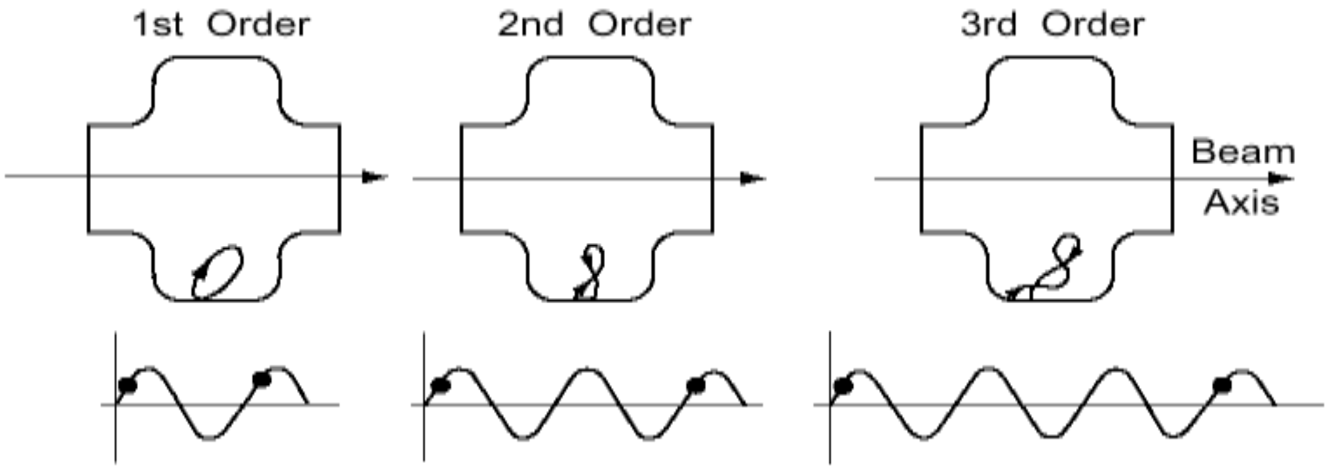
$R_S \propto exp(-\Delta/(kb\ T))$

The accelerating gradient can be limited by the peak surface electric field (field emission) or the peak surface magnetic field (quench)

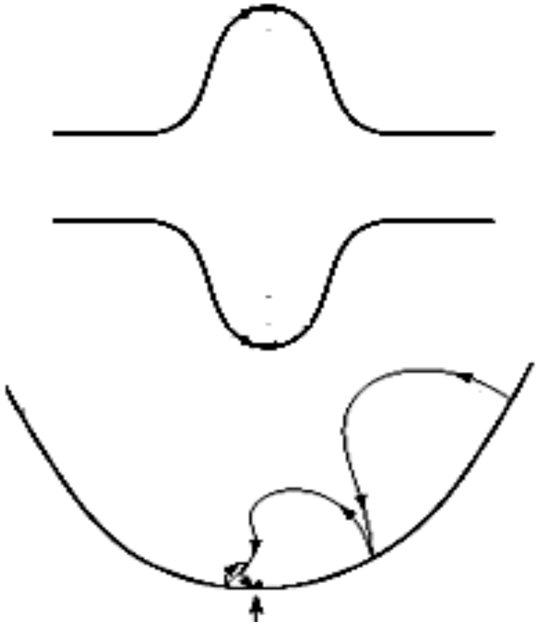


1970’s: Multipacting

Understanding:
Electron avalanche
Resonant mulitiplication due to secondary emission



High Field

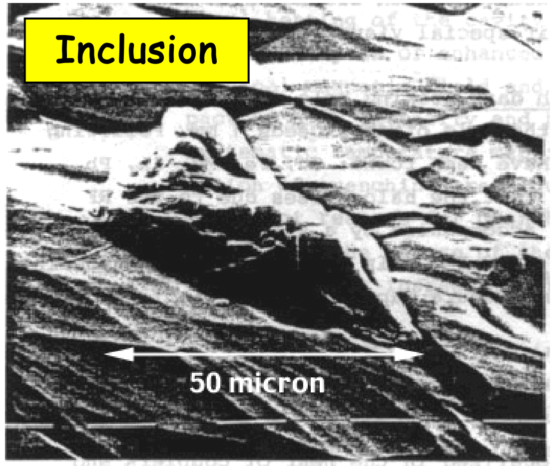


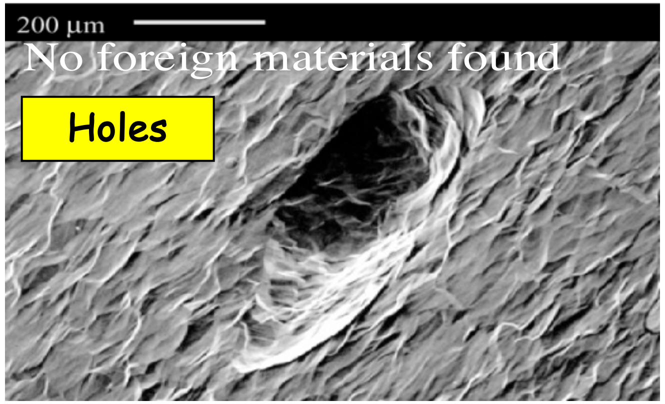
Solution: Spherical/ elliptical cavity shape

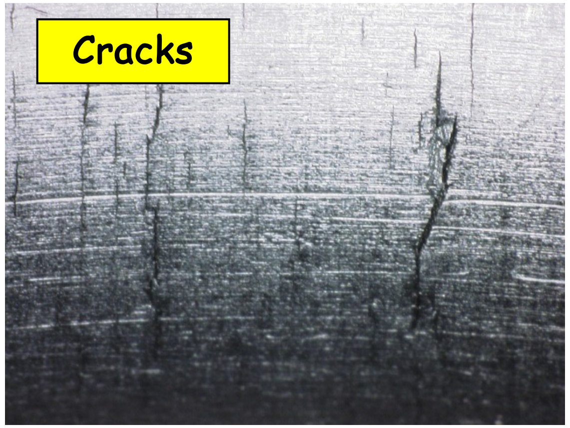
1980: Gradients rise
From 2-3 MV/m ⇒ 5 – 6 MV/m

Surface Defects Examples

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







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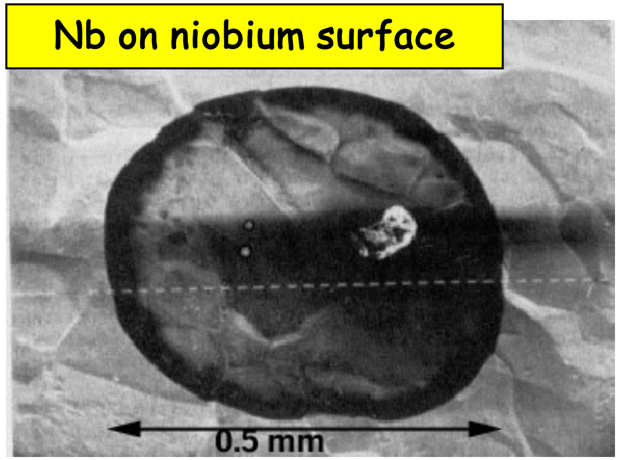
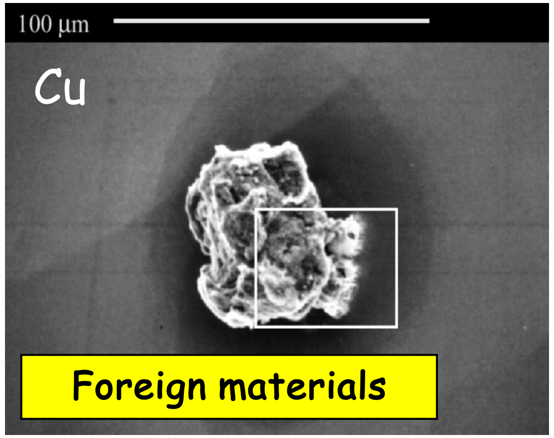
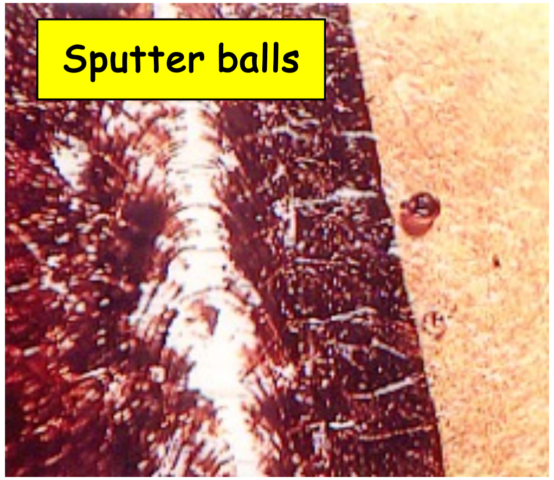


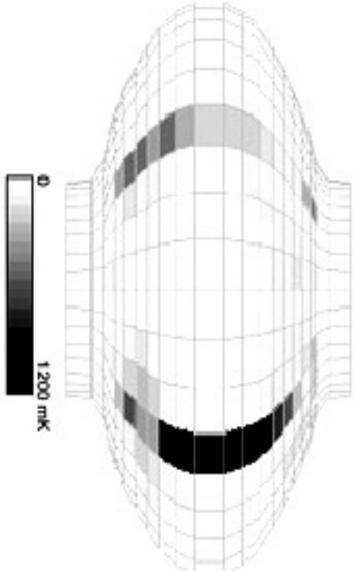




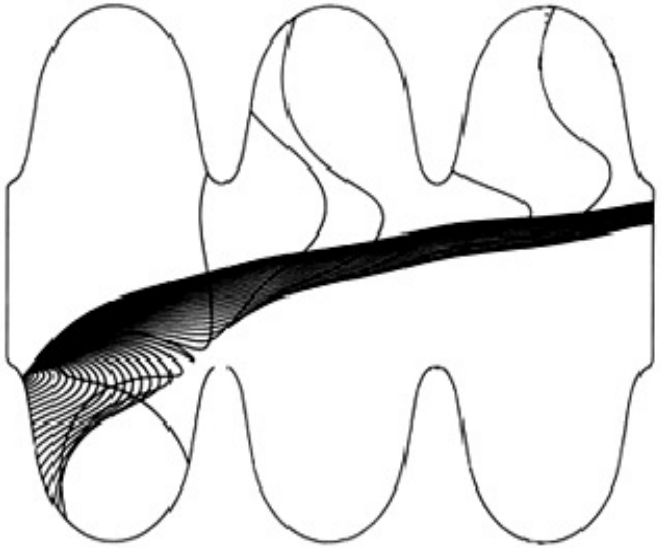
Field emission is normally caused by foreign particle contamination

- 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



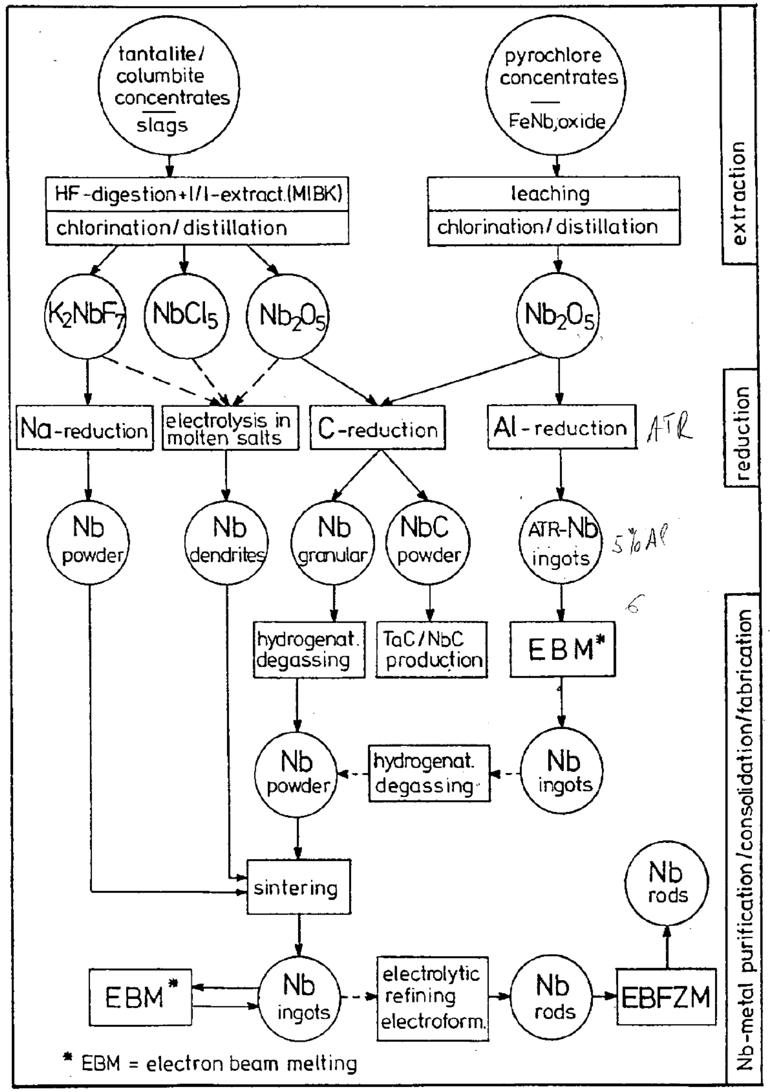
Simulation of electron trajectories in a cavity

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

The way from ore to pure Nb

The world's largest niobium deposit is located in **Araxá, Brazil** owned by Companhia Brasileira de Metalurgia e Mineração (**CBMM**). The reserves are enough to supply current world demand for about 500 years, about 460 million tons. The mining of weathered ore, running between **2.5 and 3.0% Nb_2O_5**, is carried out by open pit mining. **By chemical processes** the ore is concentrated in Nb contents (**50 –60 % of Nb_2O_5**)

Main routes of Nb fabrication process



Classical routes for Nb, consist of the carbothermic reduction of Nb_2O_5 and the aluminothermic reduction of Nb_2O_5 followed by EBM.

$$Nb_2O_5 + 7C \rightarrow 2NbC + 5CO$$

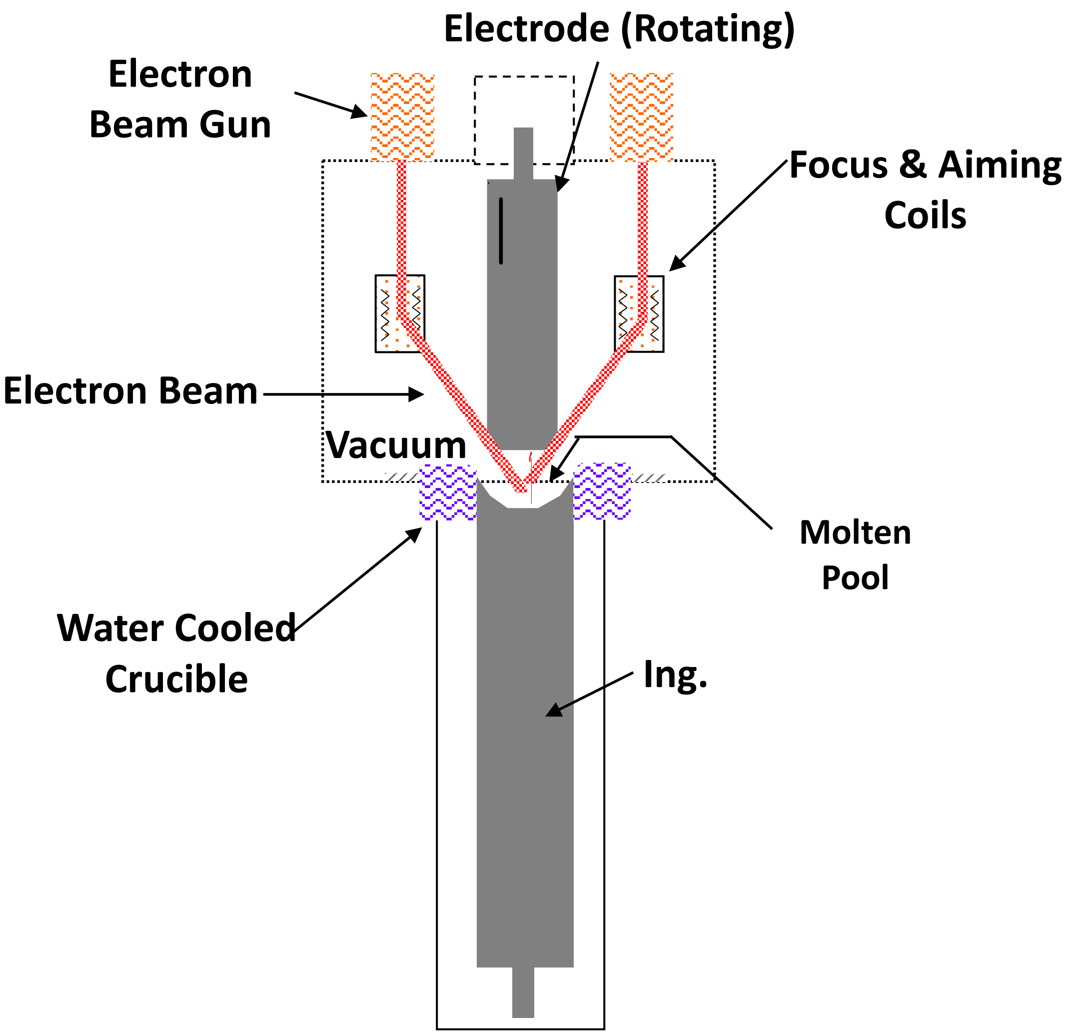
$$5NbC + Nb_2O_5 \rightarrow 7Nb + 5CO$$

$$3Nb_2O_5 + 10Al \rightarrow 5Al_2O_3 + 6Nb$$

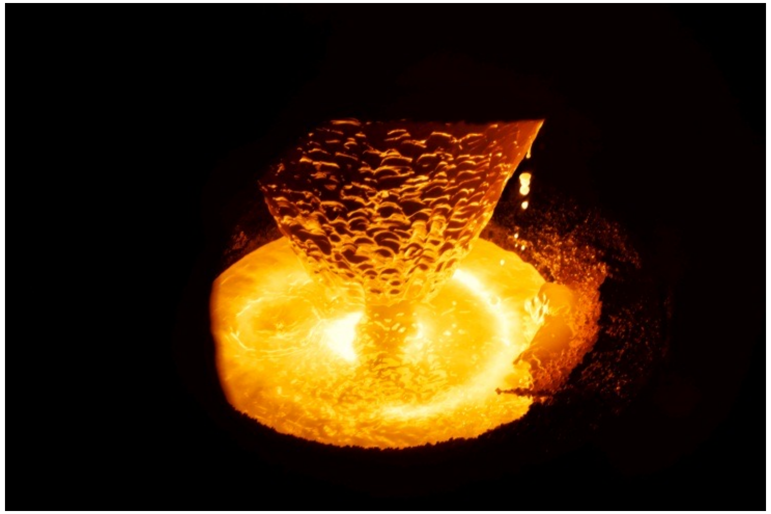
An alternative route of niobium fabrication and alloying is powder metallurgy. For special applications it may be convenient to produce powder with high purity hydriding. The production of high-grade niobium with small Ta-concentration can be performed via the sodium reduction of purified K_2NbF_7.

$$K_2NbF_7 + 5Na \rightarrow Nb + 2KF + 5NaF$$

Electron Beam Melting of Niobium



During of the ingot melts, molten metal globules **fall into a pool** on the ingot which is contained in a water cooled copper crucible. Impurities are evaporated and pumped away. Power impact is maintained to keep the pool molten out to within a few mm of the crucible wall. During melting the ingot formed is **continuously withdrawn** through the crucible.



Electron Bem Melting

As a result of the increasing demand for refractory metals in the last few decades, the electron-beam furnace has been developed to a reliable, efficient apparatus for melting and purification.

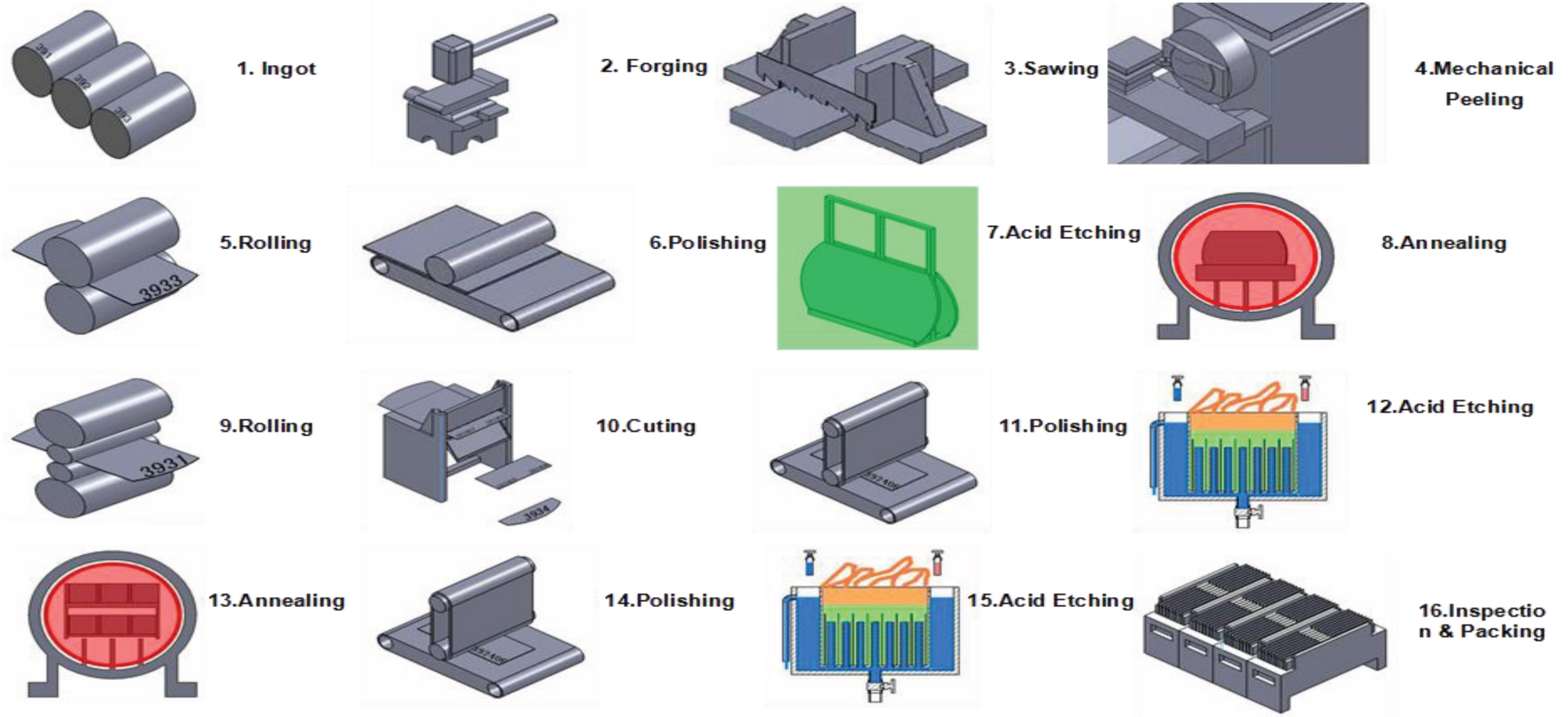
One problem sometimes observed with e-beam melted ingots is the nonhomogeneous distribution of impurities. The **skin** of the ingot contains more impurities than the inside. **Top to bottom inhomogeneity**.

Nb Sheets Fabrication at OTIC

1. Introduction of production process

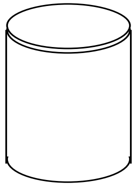
Nb300 Sheet

东方钽业 OTIC
中国有色集团成员企业

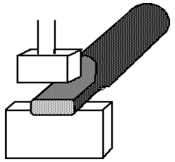


www. otic. com. cn

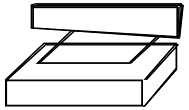
Nb Sheets Fabrication at Tokyo Denkai



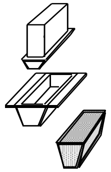
Mother material



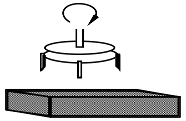
Forging



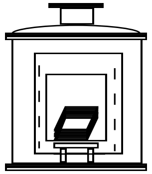
Cutting



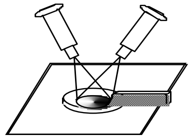
Pressing



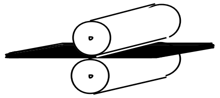
Milling



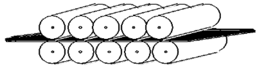
Annealing



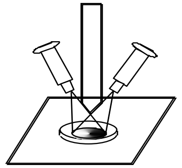
1st EB melting



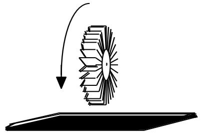
Rolling



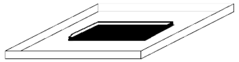
Levering



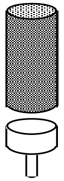
2nd, 3rd etc. EB melting



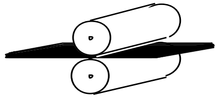
Polishing



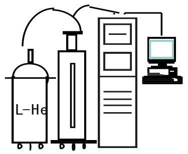
Chemical polishing



Separate from base plate



Rolling



Inspection

Other Physical Limits

Critical Magnetic Field Limit

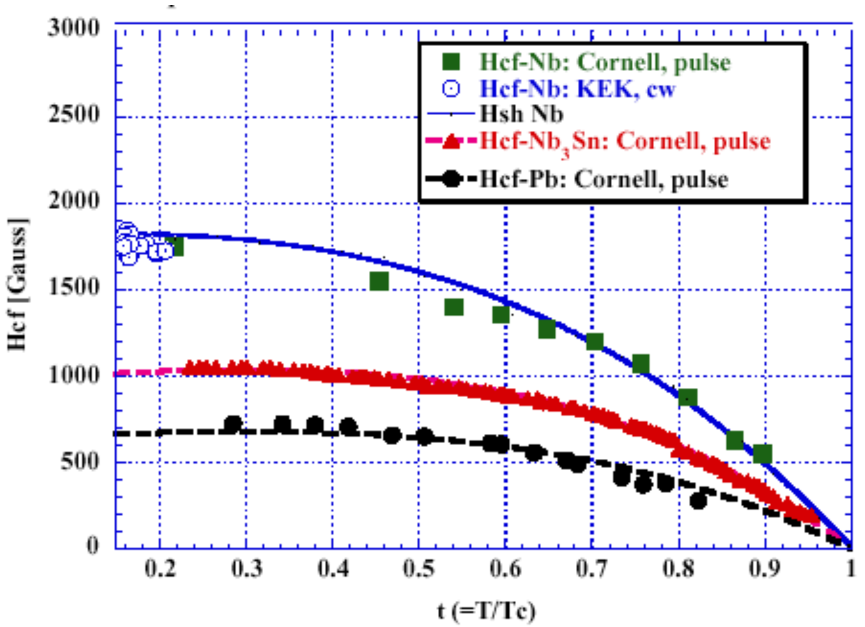
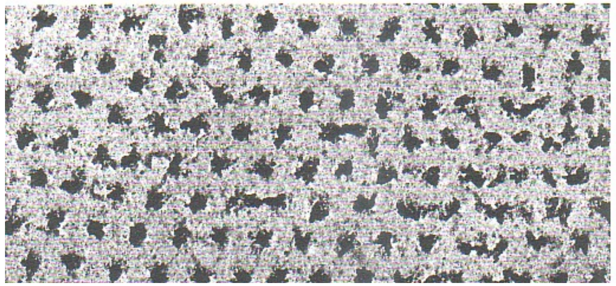


Figure 10: Critical RF fields (Hcf) of sc cavities and Hsh.

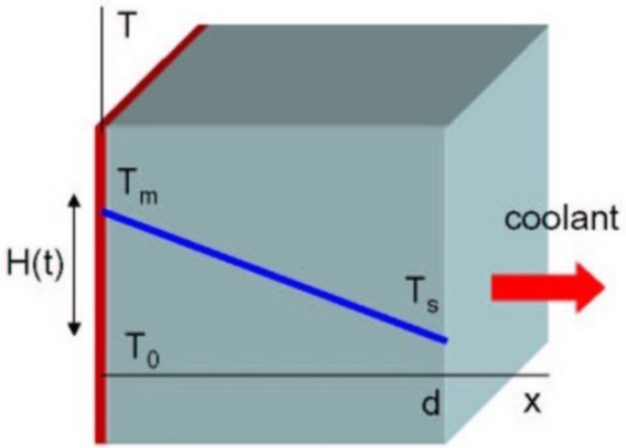
$B_{max} \leq 180\ mT$

Vortex state of trapped Magnetic Field



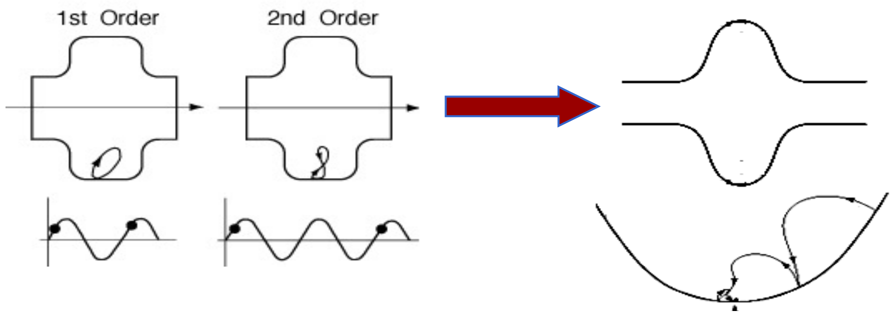
Limited thermal conductivity

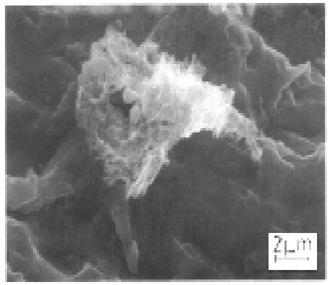
- Thermal Conductivity of the bulk Nb
- Kapitza resistance at the surface

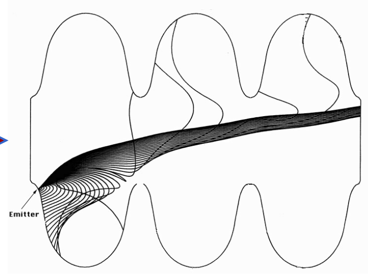


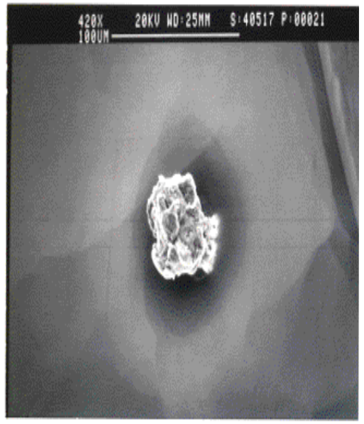
Synthesis: R&D waiting for big projects

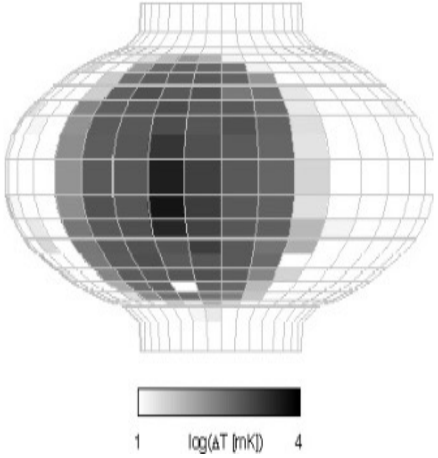
- **Understanding Multipactoring**
  - A few computer codes developed
  - Spherical shape realized at Genova and qualified at Cornell & Wuppertal
- **Understanding Field Emission**
  - Emitters were localized and analyzed
  - Improved treatments and cleanness
- **Cure thermal Breakdown**
  - Higher RRR Nb
  - Deeper control for inclusions



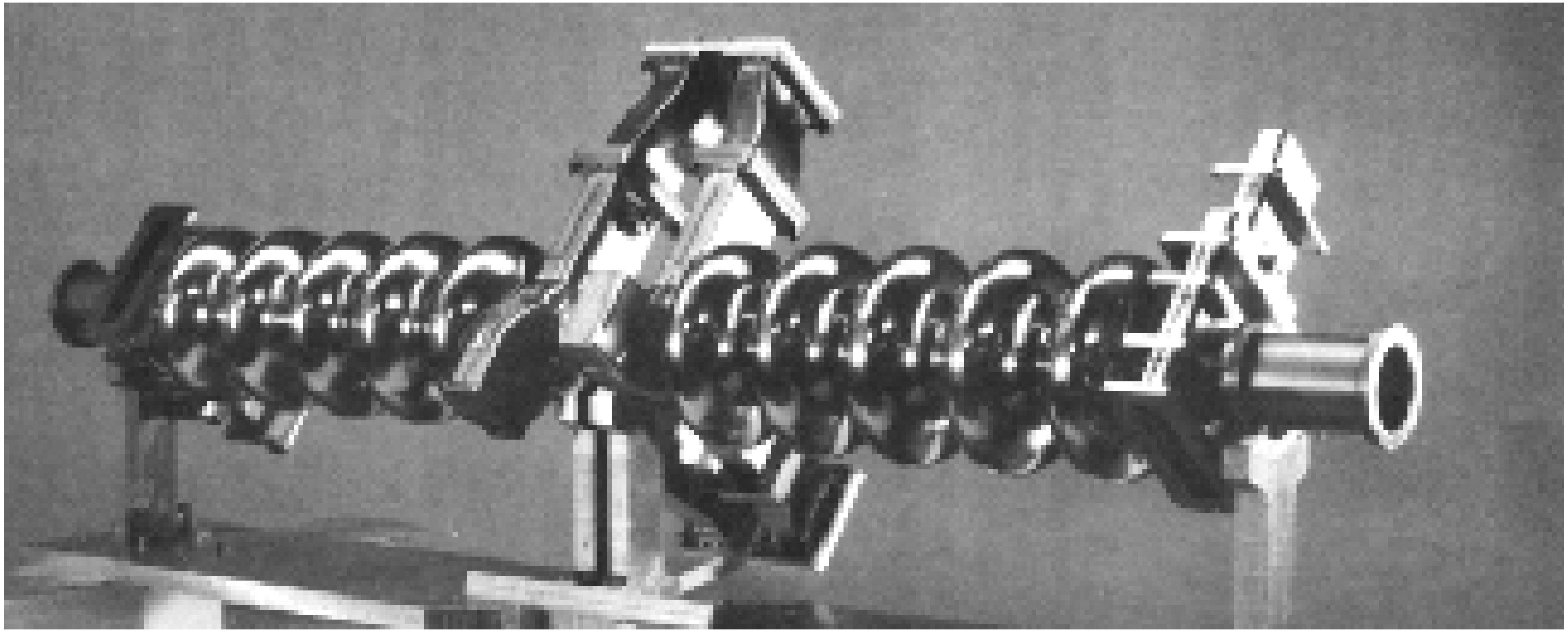








1984/85 The Cornell Brake-throug



First great success

A pair of 1.5 GHz cavities developed and tested at Cornell: 4.5 MV/m

Chosen for CEBAF at TJNAF for a nominal E_{acc} = 5 MV/m

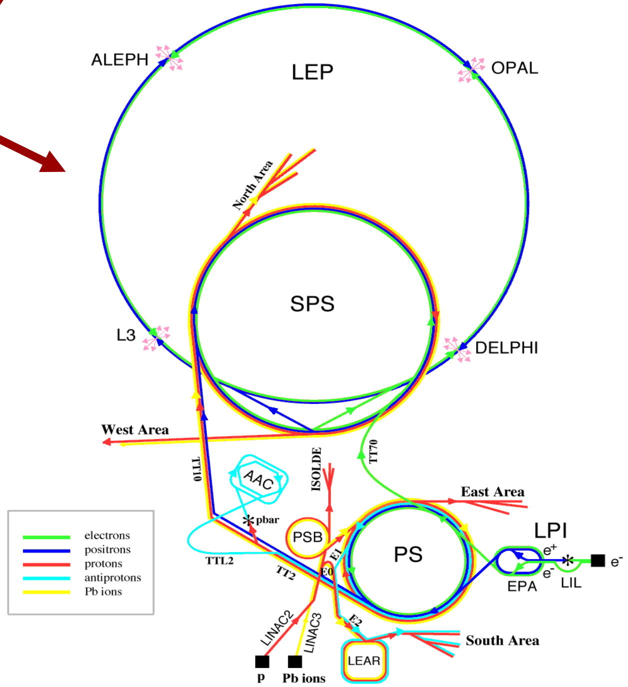
Contents

1. Introduction
2. From the Pioneering Age to the big Projects
3. The explosion driven by the big Projects
4. The TESLA Collaboration and its impact

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)



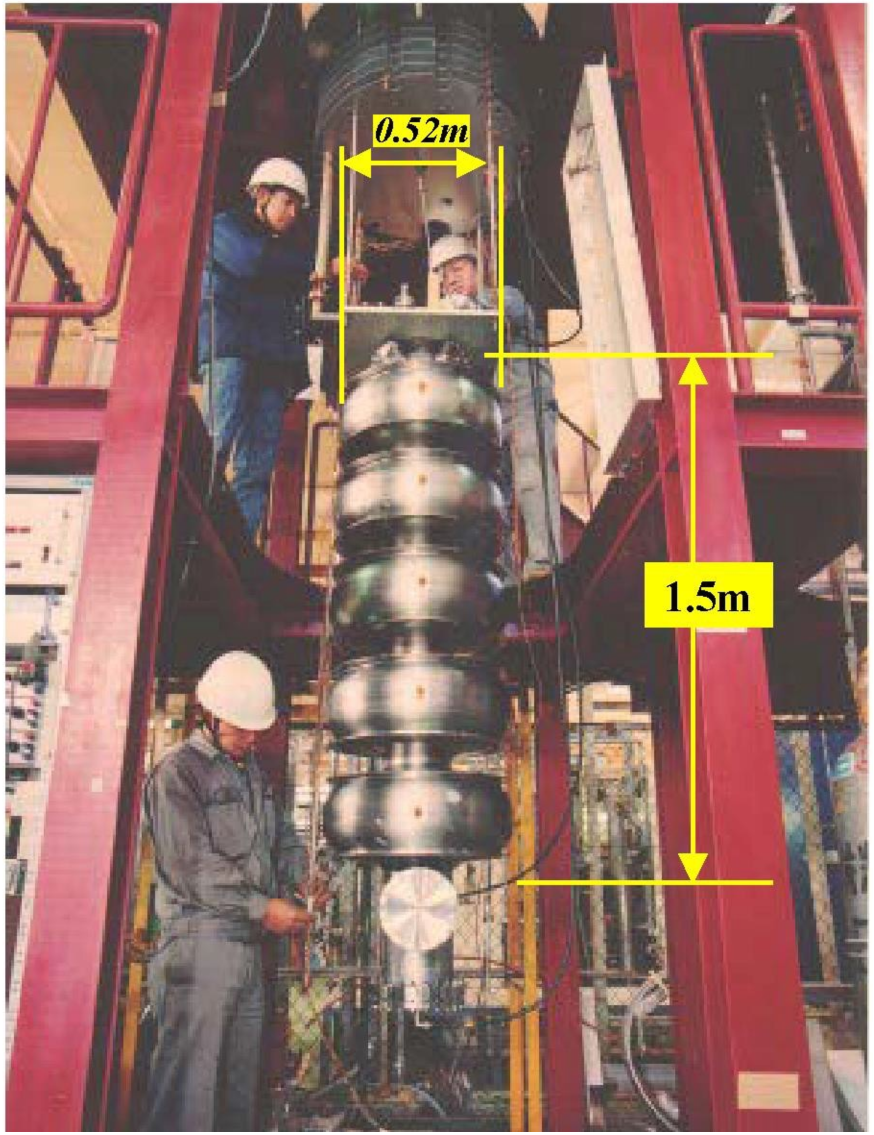
Multi-cell, β = 1, cavities for recirculating linacs

- **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 **KEK, TJNAF and CERN played the major role** in SRF development, mainly because of 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**

First Industrial Production in Japan *(1988 – 1995)*

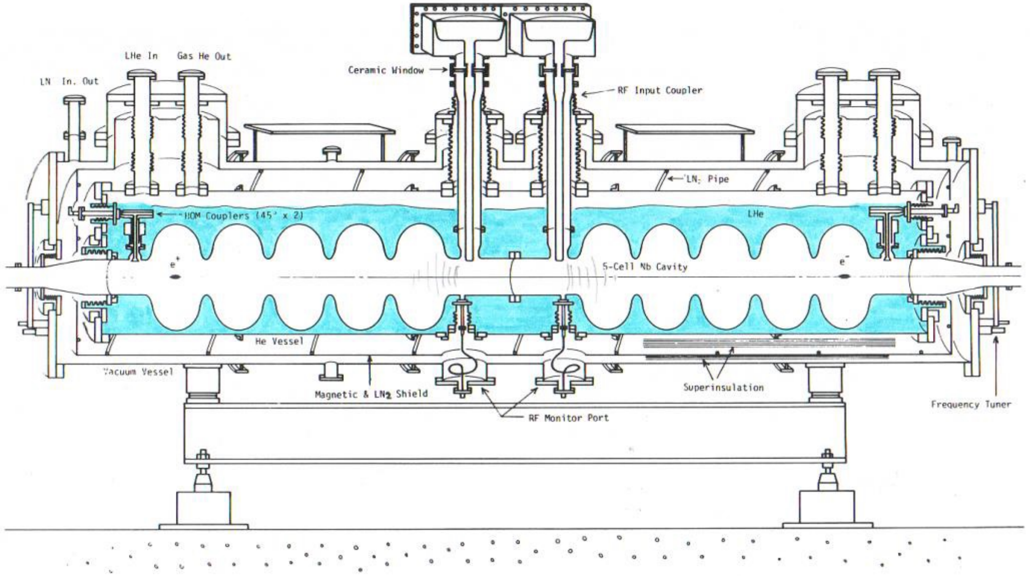


The **first mass-production** of SRF Cavities in the world

SRF Cavity **for TRISTAN** at **KEK**

Bulk-Nb - 508MHz - 5-Cell Cavity

32 SRF cavities were fabricated by Mitsubishi and operated in TRISTAN



TRISTAN SRF from KEK to MHI

KEK 1981

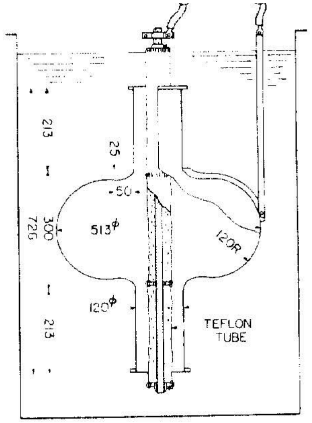


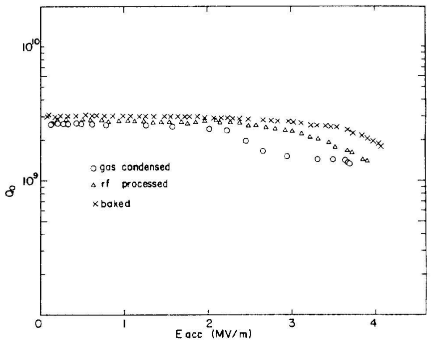
Fig. 1 Set up of the electropolishing.

Major impurities in the niobium used for the 500 MHz cavity.

Tantalum	1700 ppm
Tungsten	800 ppm
Zirconium	800 ppm
Silicon	500 ppm

T. Furuya, S. Hiramatsu, T. Nakazato, T. Kato
P. Kneisel*, Y. Kojima and T. Takagi

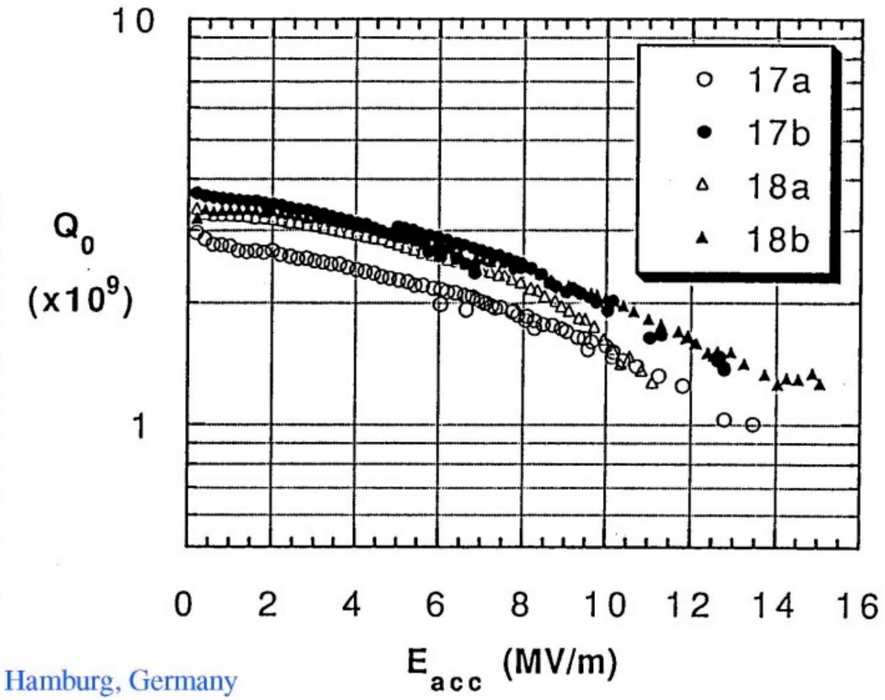
IEEE Transactions on Nuclear Science, Vol. NS-28, No. 3, June 1981



1995

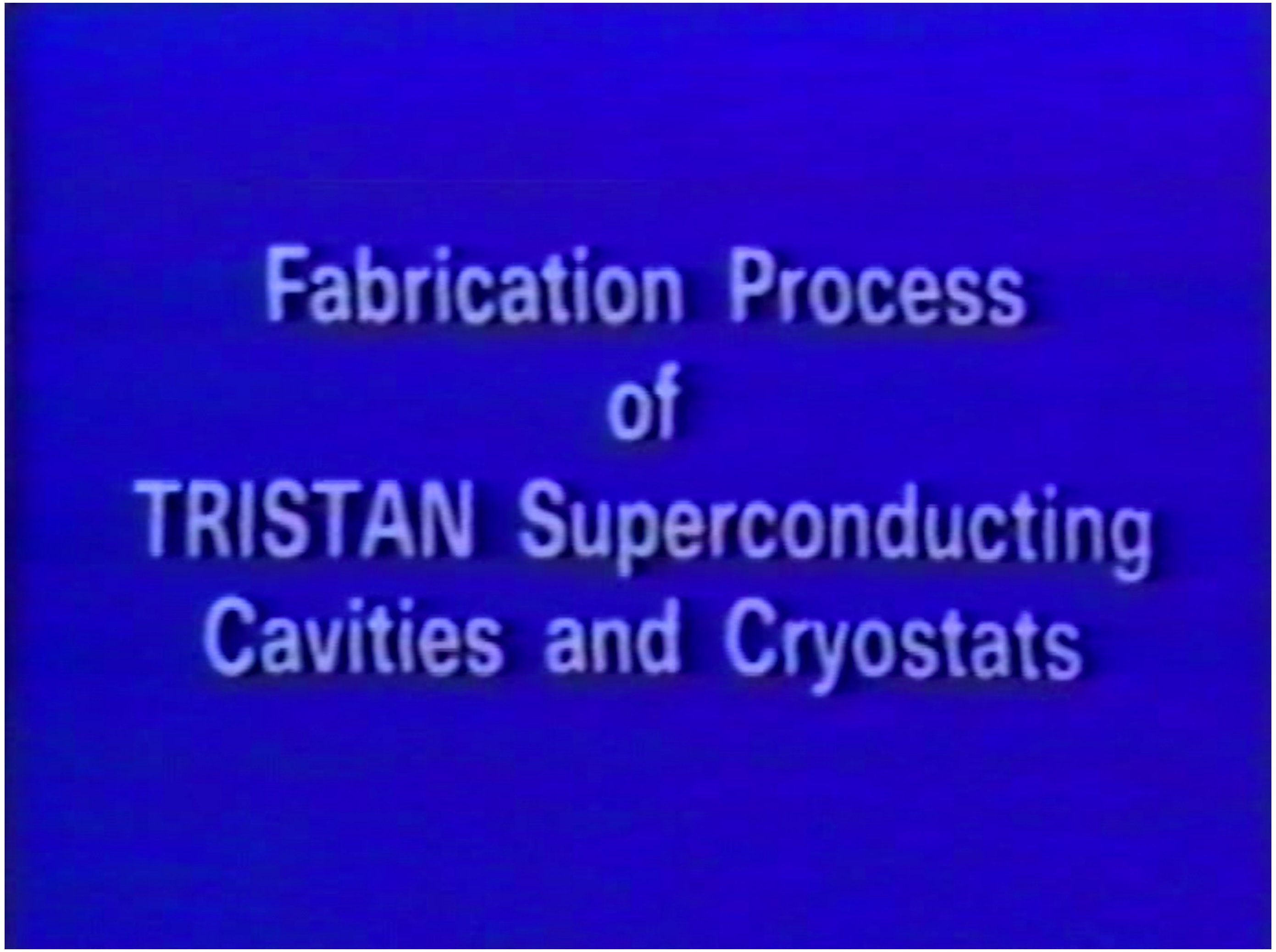
Table 1. Results of final vertical measurements of spare cavities.

Cavity #	17a	17b	18a	18b
Meas. date	28 June 91	12 June 91	30 Jan. 91	7 Feb. 91
f_0 (MHz)	508.240	508.178	508.204	508.218
Q_{15D}[1) ($\times 10^{11}$)	3.33	2.57	2.49	3.03
Q_0 at low field ($\times 10^9$)	2.8	3.6	3.3	3.4
$E_{acc,max}$ (MV/m)	13.5	12.8	11.1	15.1



Proceedings of the Fifth Workshop on RF Superconductivity, DESY, Hamburg, Germany

TRISTAN Cavities Fabrication (1986)



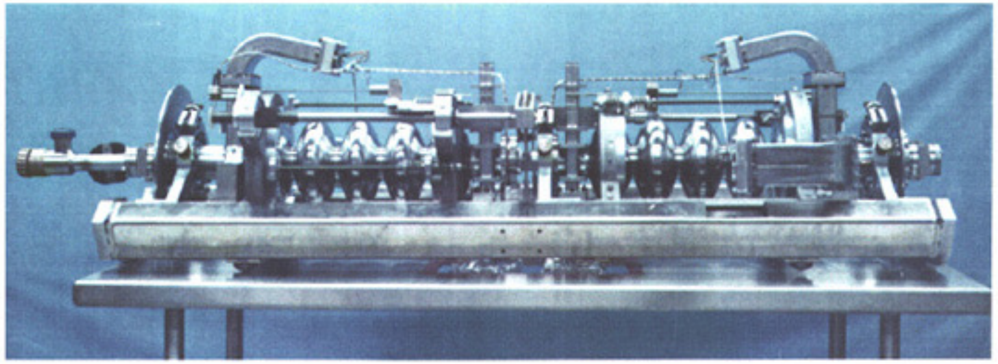
Original KEK Movie of the full cycle for the production and test of the TRISTAN SRF System, including

- complete production cycle of one of the TRISTAN SC Cavities at Mitsubishi
- Cavity vertical test at KEK
- Two cavity cryomodule assembly
- Cryomodule horizontal test in a bunker

CEBAF Recirculating Linac

Aerial view of the CEBAF site

A pair of 5-cell 1.5 GHz CEBAF cavities



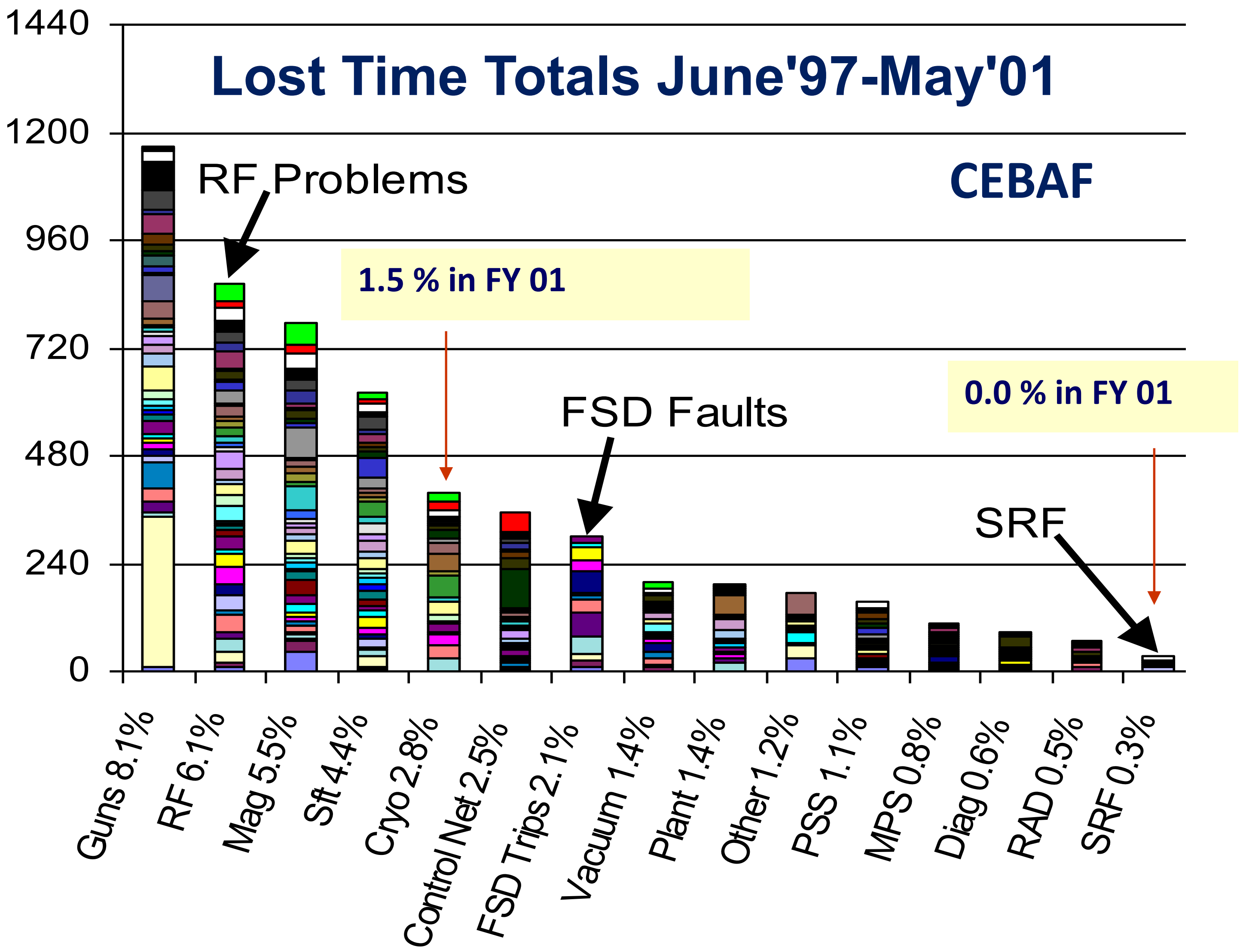
CEBAF important achievements

- First large recirculating linac
- Large cryogenic plant at 2 K
- R&D on fabrication and treatments for Nb
- Large plants for preparation and RF tests
- Great experience on SRF linac operation
- Excellent SRF reliability demonstrated
- Set the background for SNS

Lessons learned from 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

A great success for CEBAF



Excellent reliability of SRF technology

High availability for physics

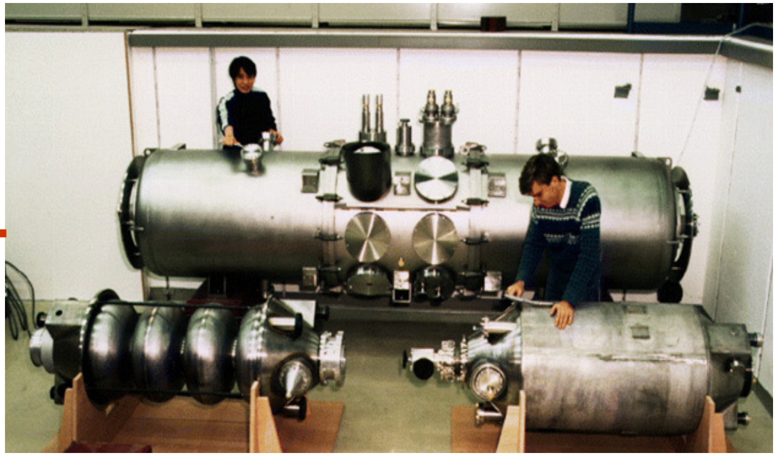
The only warm-up for the **Isabelle Hurricane**

LEPII and HERA

4-cell, 352 MHz, L_{act}=1.7 m

32 bulk niobium cavities
- Limited to 5 MV/m
- Poor material and inclusions

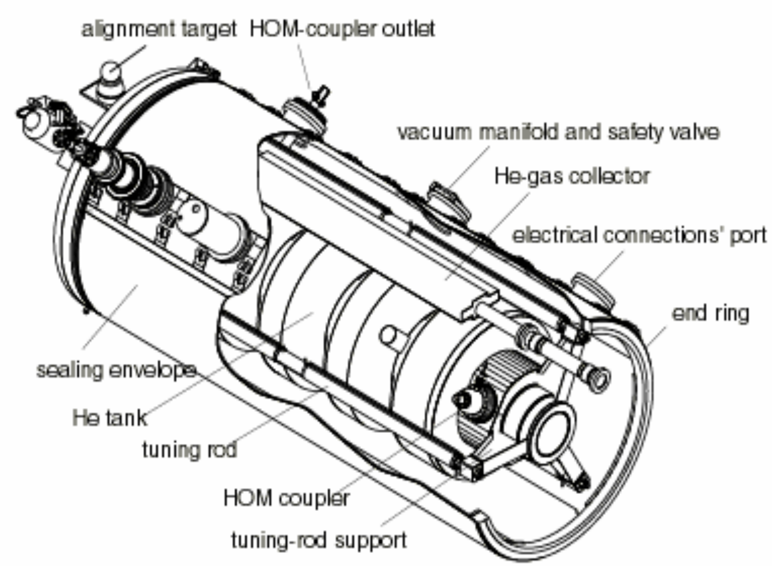
256 sputtered cavities
- Magnetron-sputtering of Nb on Cu
- Completely done by industry
- Moderate Q-slope at 350 MHz
- Field emission above 8 MV/m
- Average E_{acc} = 7.8 MV/m – cryo-limited

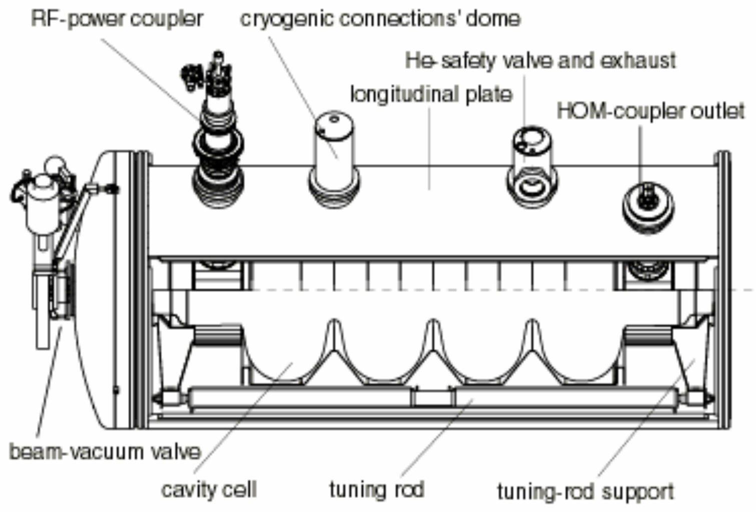


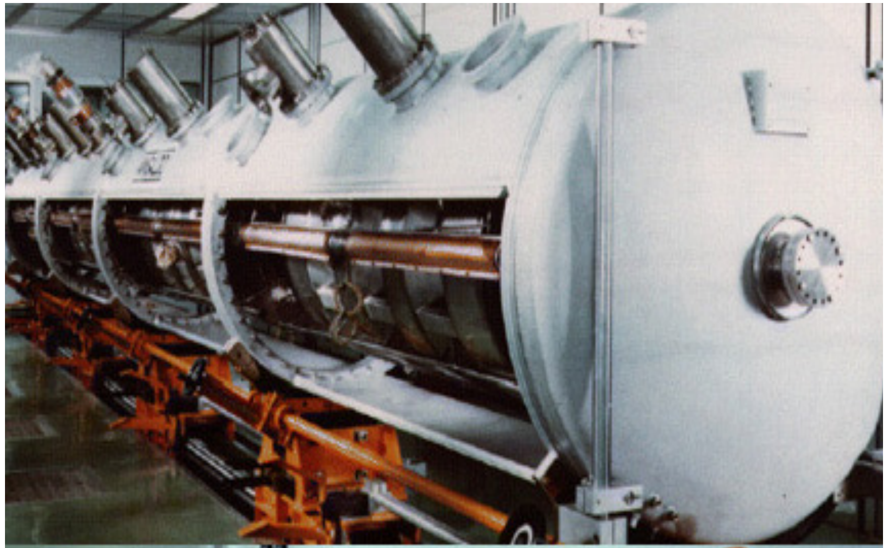
4-cell, 500 MHz, L_{act}=1.2 m

16 bulk niobium cavities
- Limited to 5 MV/m
- Poor material and inclusions
- Q-disease for slow cooldown
- In HERA power coupler limited

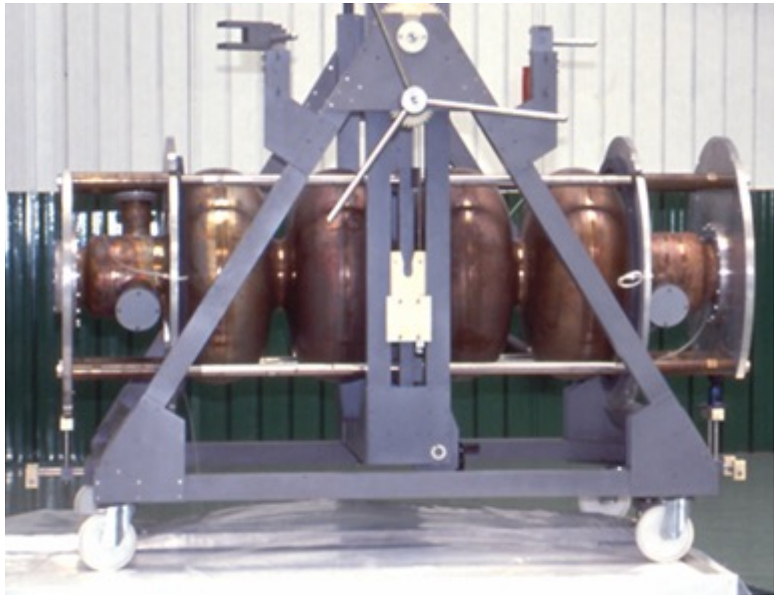
LEP 2 Cavities and Modules

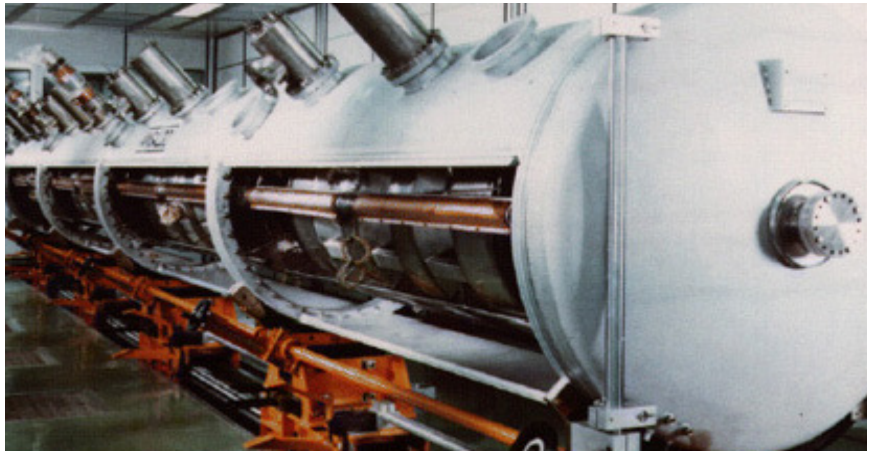






LEP-2 Cavities in Industry



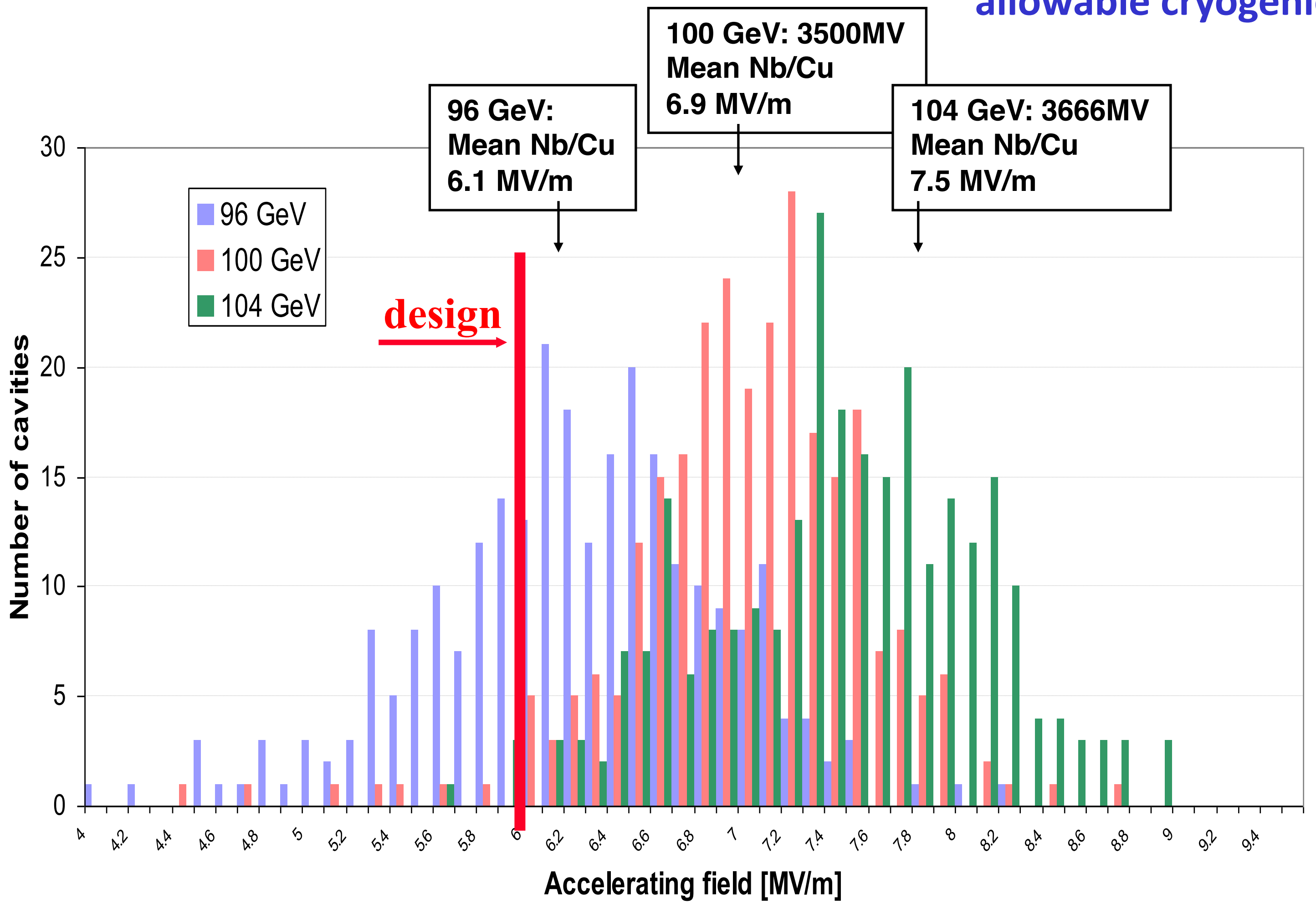


A great success for LEP II

Accelerating Field Evolution with time

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

Final energy reach limited by allowable cryogenic power



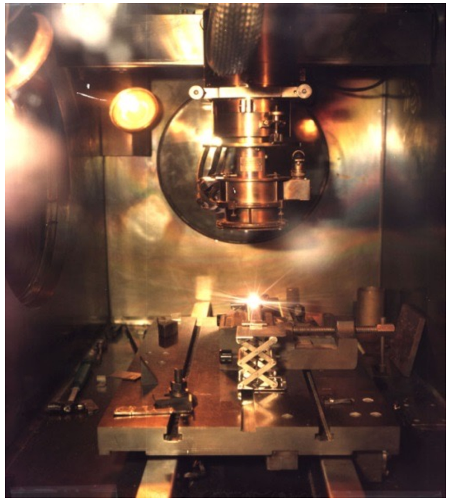
Installed Cryomodules

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

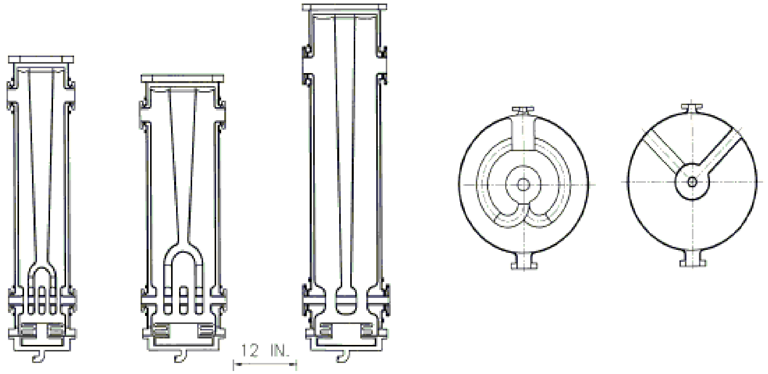
- Final cleaning and drying (UV for bacteria and on line resistivity control)
- Integration of cavity ancillaries

That is

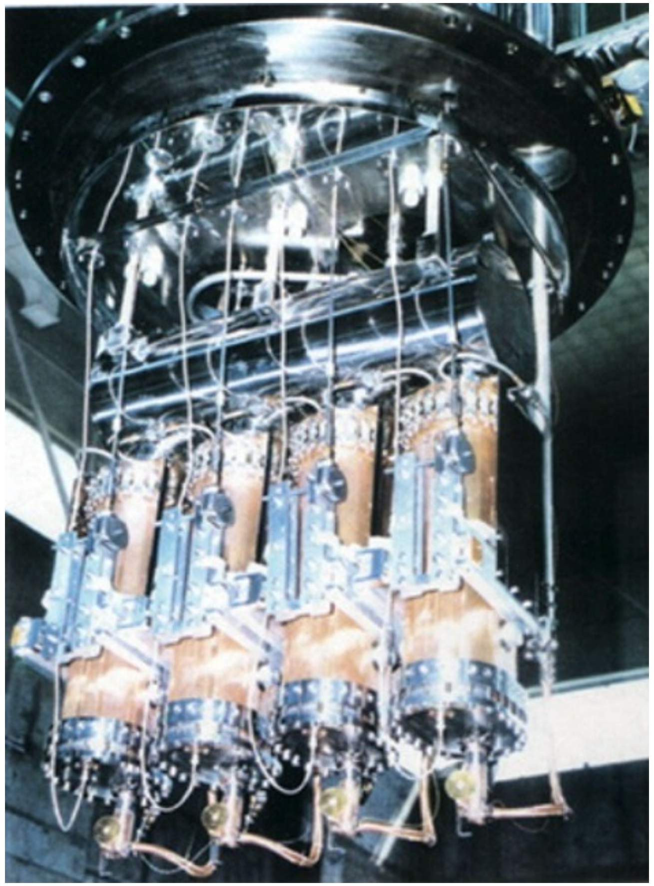
New level on Quality Control

New linacs for Heavy Ions

- New Projects
  - Stony Brook
  - JAERI,
  - Washington University
  - Argonne upgrade,
  - Legnaro
- Improved cavity designs



- Higher accelerating fields, limited by:
  - Microphonics
  - No beam vacuum separation



Group of four Quarter-wave cavities for the JAERI Heavy-ion Linac

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 up to be a plus

For high gradient, $\mathbf{E_{acc}}$, 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

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1. Introduction
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The TESLA Collaboration

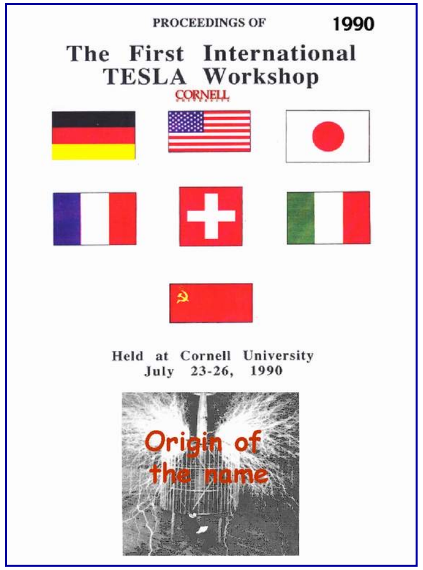
Develop SRF for the future TeV Linear Collider

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

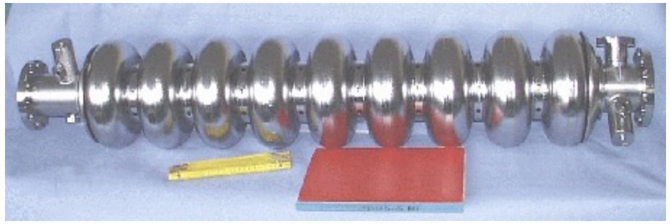
- **Higher conversion efficiency**: more beam power for less plug power consumption
- **Lower RF frequency**: relaxed tolerances and smaller emittance dilution

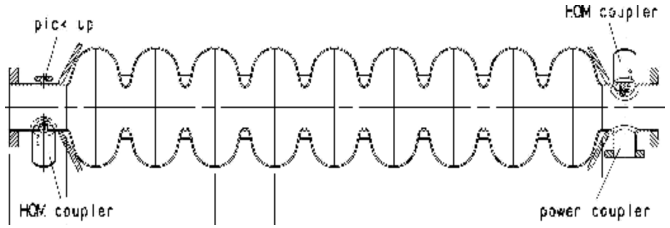


First Steps of the TESLA Game

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

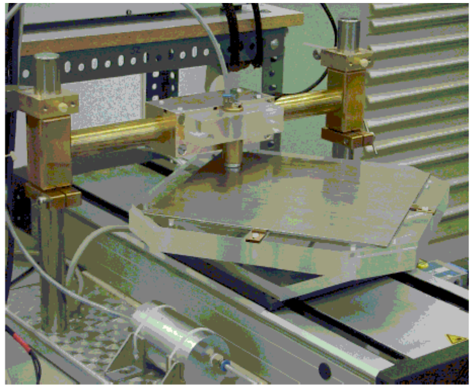
9-cell, 1.3 GHz





TESLA cavity parameters

R/Q	1036	W
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	$Hz/(MV/m)^2$



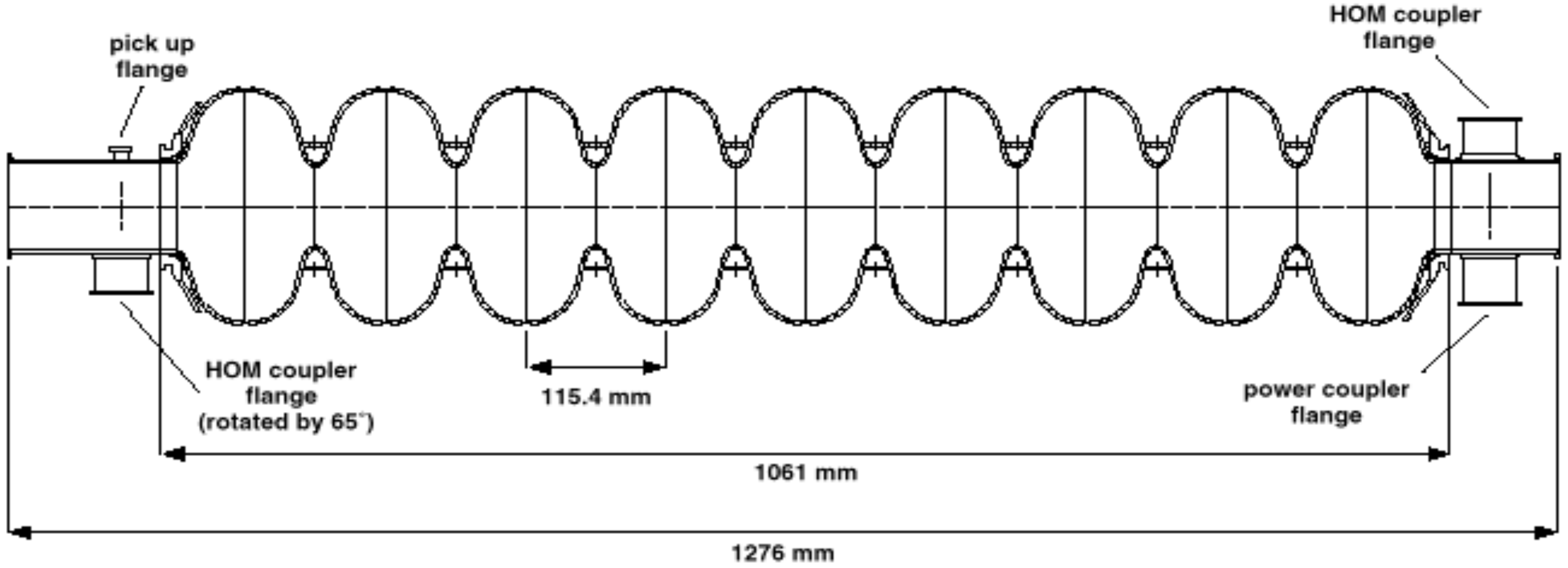
Eddy-current scanning system for niobium sheets

Cleanroom handling of niobium cavities

Preparation Sequence

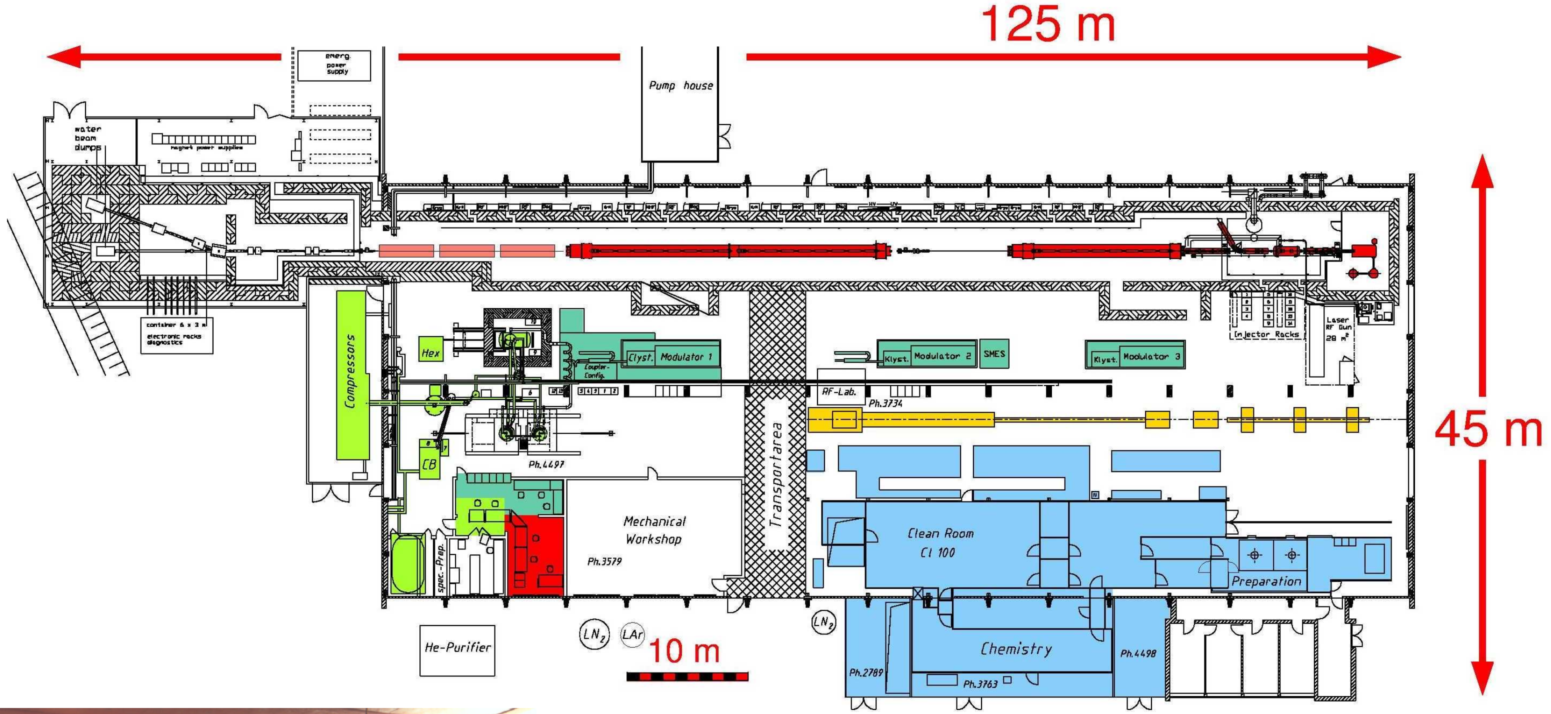
- Niobium sheets (RRR=300) are scanned by eddy-currents to detect avoid foreign material inclusions like tantalum and iron
- Industrial production of full nine-cell cavities:
  - Deep-drawing of subunits (half-cells, etc.) from niobium sheets
  - Chemical preparation for welding, cleanroom preparation
  - 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

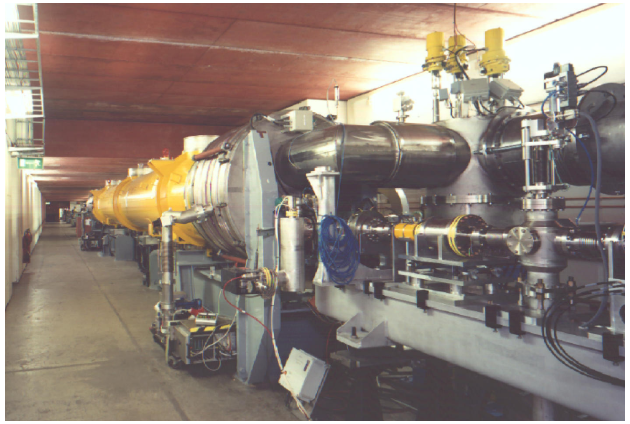
TESLA cavity design and rules

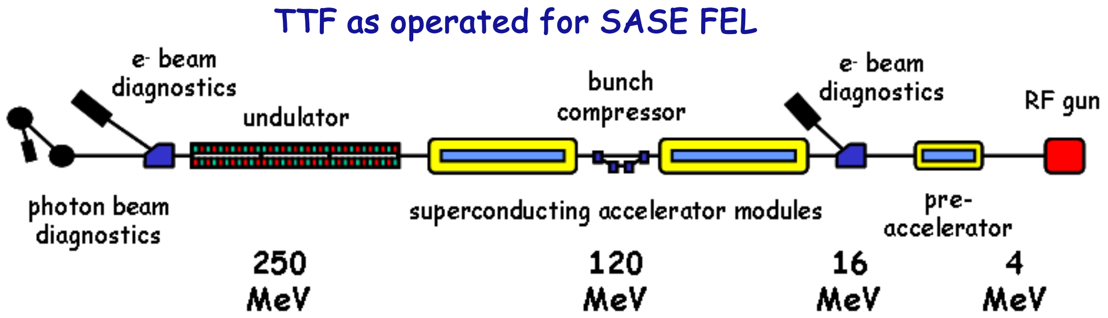


type of accelerating structure	standing wave
accelerating mode	TM0 π mode
fundamental frequency	1300 MHz
design gradient E_{acc} (TTF)	15 MV/m
design gradient E_{acc} (TESLA)	25 MV/m
unloaded quality factor Q_0 (TTF)	$> 3 \times 10^9$
unloaded quality factor Q_0 (TESLA)	$> 5 \times 10^9$
shunt impedance 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

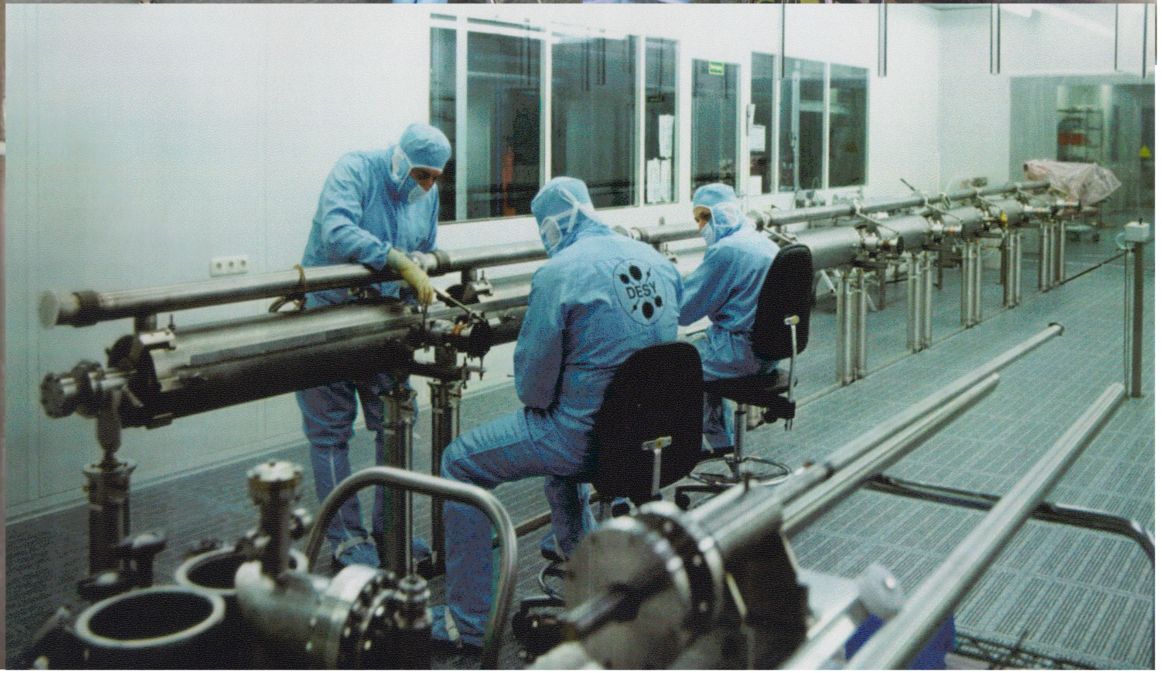
TTF: a new infrastructure at DESY





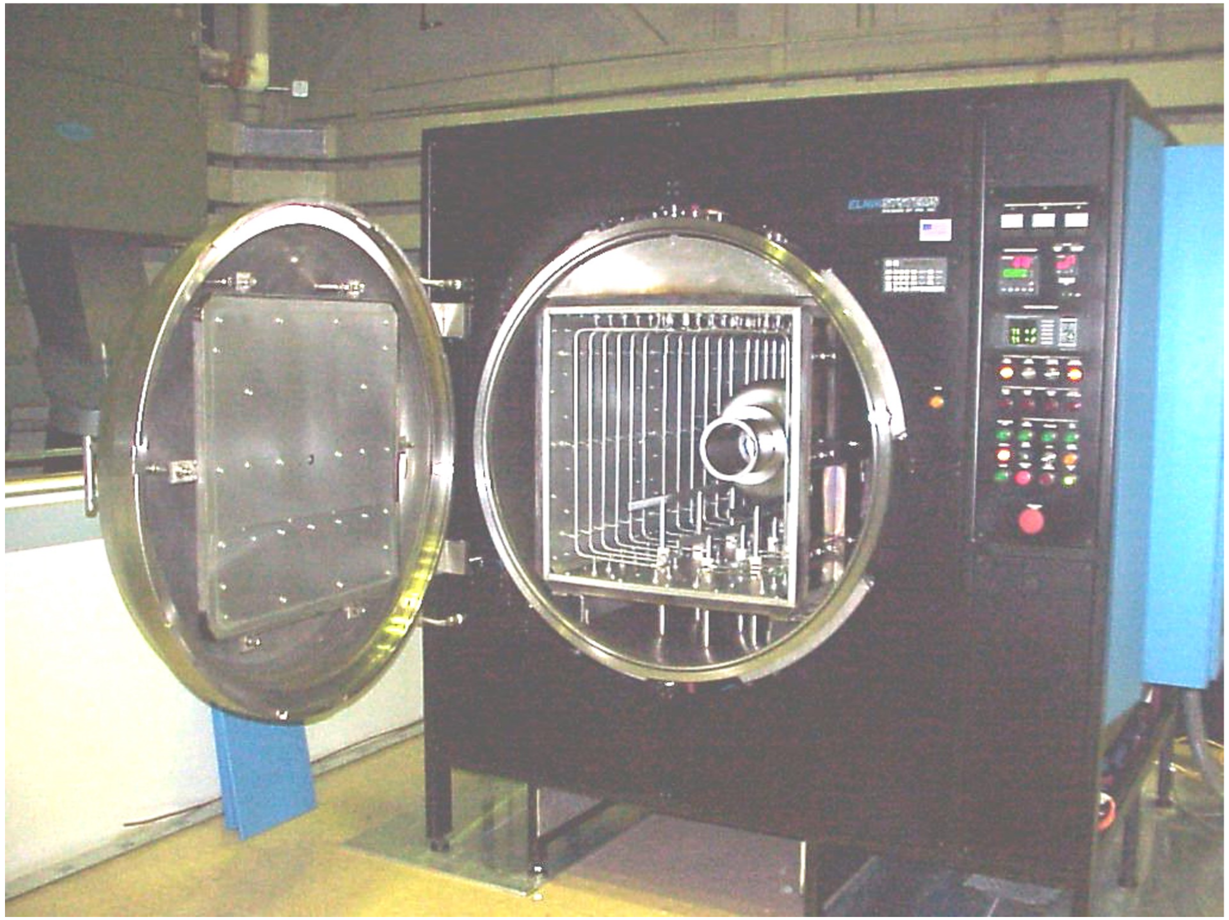


Preparation of TESLA Cavities

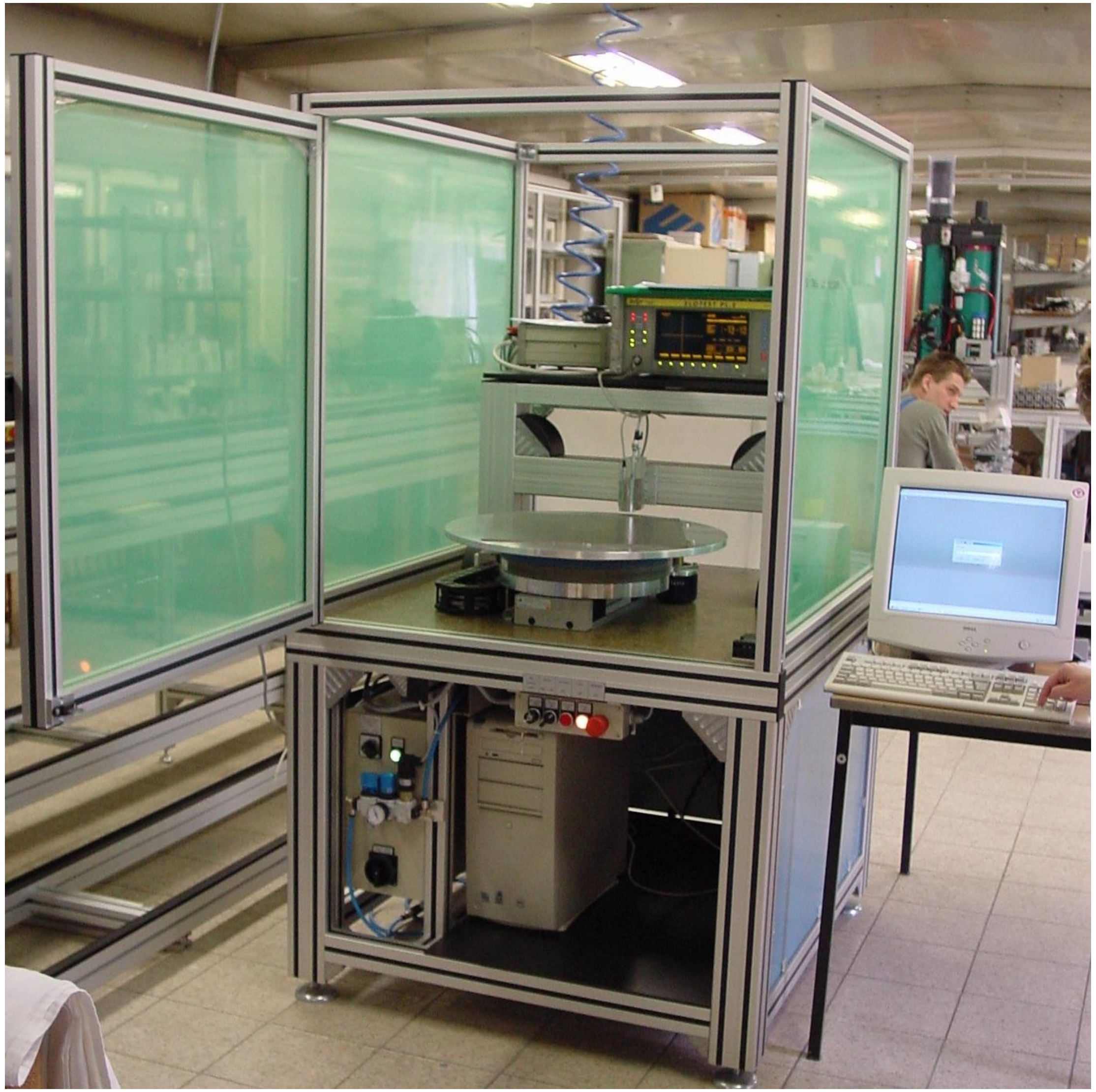


High Temperature for RRR Improvement

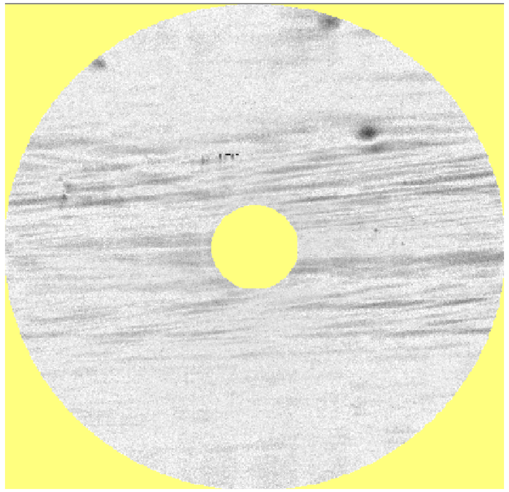
Heat Treatment Furnace at Jlab up to 1400C, reproduced at DESY



Eddy Current Scanner for Nb Sheets



Scanning results

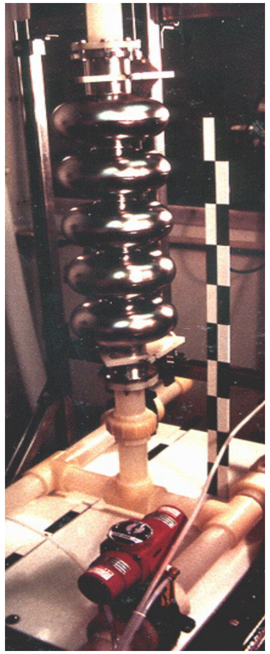


- Rolling marks and defects are visible on a niobium disk to be used to print a cavity half-cell.
- Surface analysis is then required to identify the inclusions

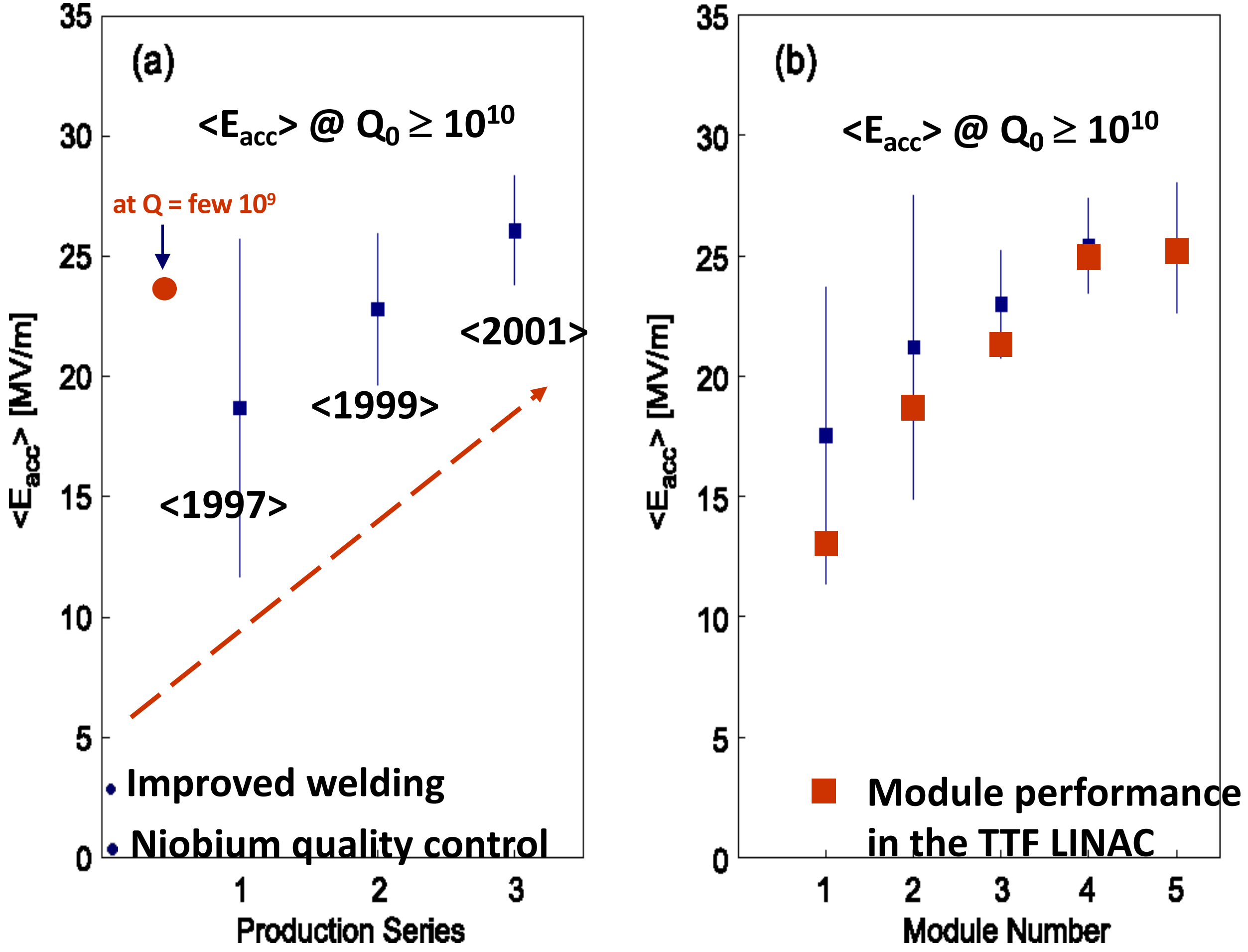
Learning curve with BCP

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

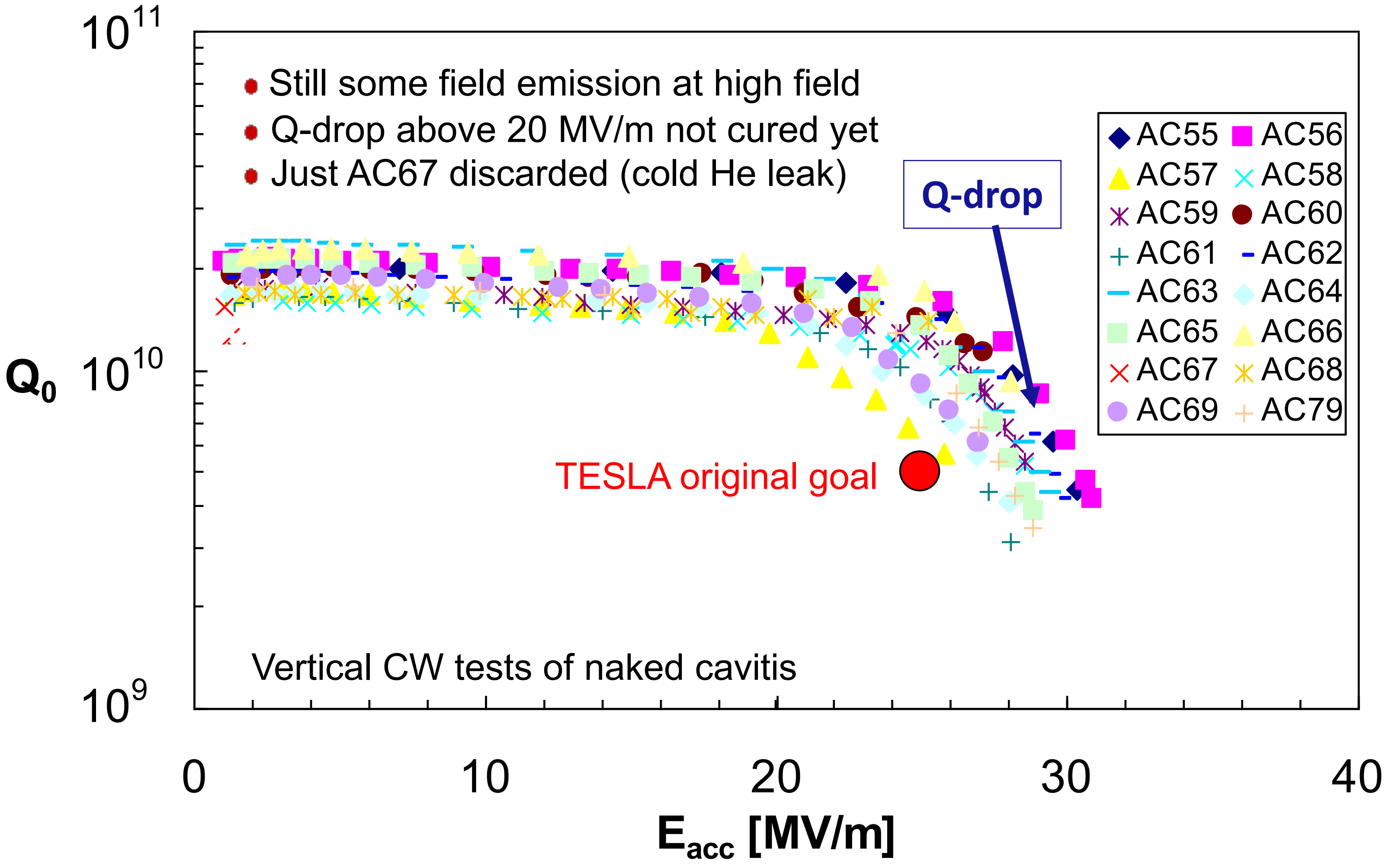
Cornell ● 1995



5-cell



3rd cavity production with BCP



Two major contributions for higher field

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

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

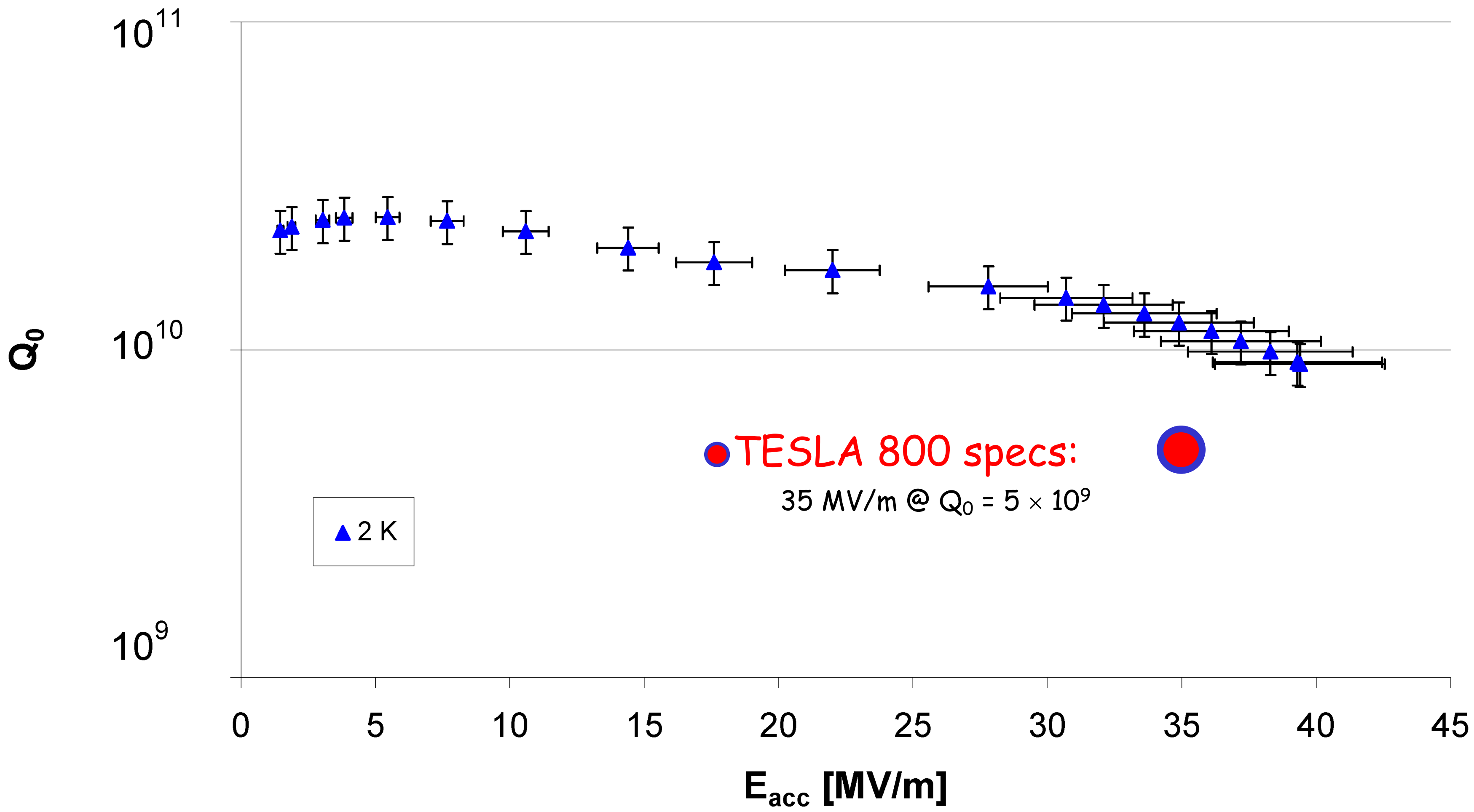
Electro-polishing (EP) from KEK (**Kenji Saito**)

Improves field emission and maximum field

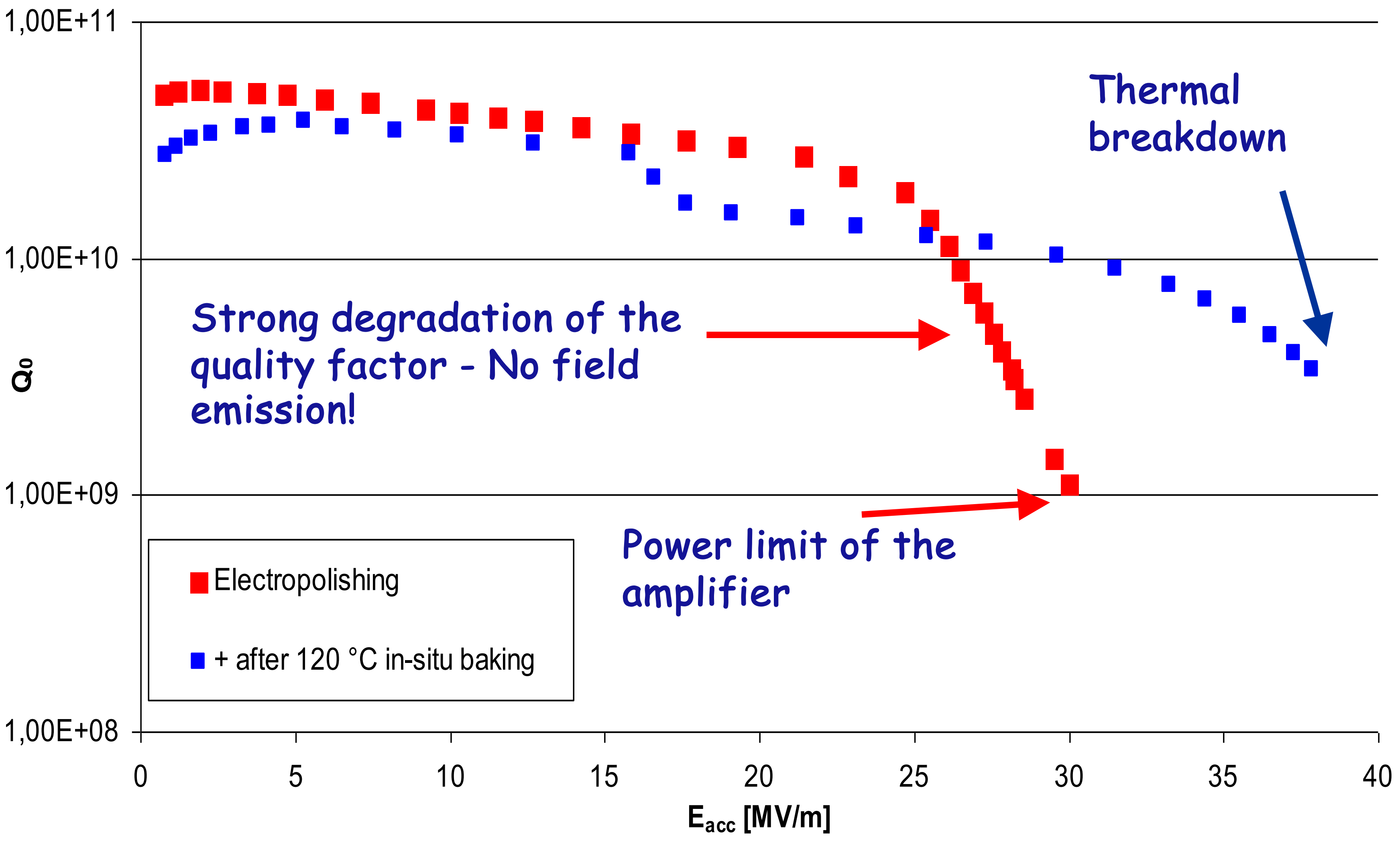
- Much smoother surface, less local field enhancement
  - Better cleaning with high pressure water rinsing
  - Q-drop cure by in-situ baking more efffective
  - High temperature (1250 °C) heat treatment avoidable

Results on AC70 – 1 (2004)

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



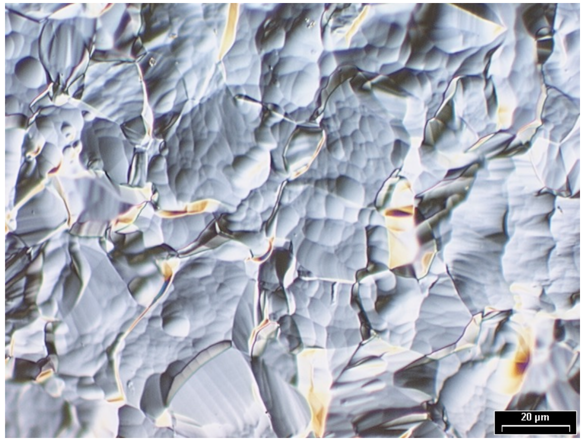
In-situ Baking effect



Electro-Polishing for 35 MV/m

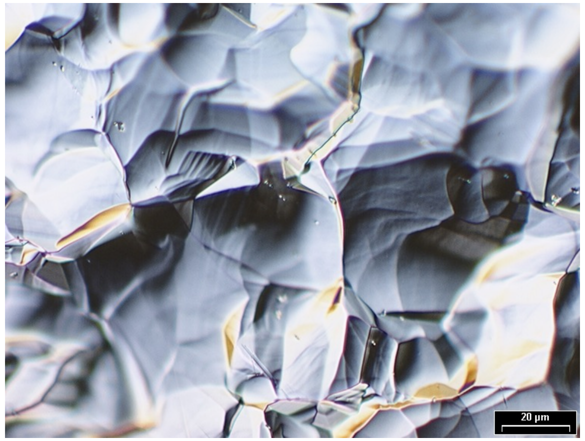
Coordinated R&D effort: DESY, KEK, CERN and Saclay

Nb sheet as delivered

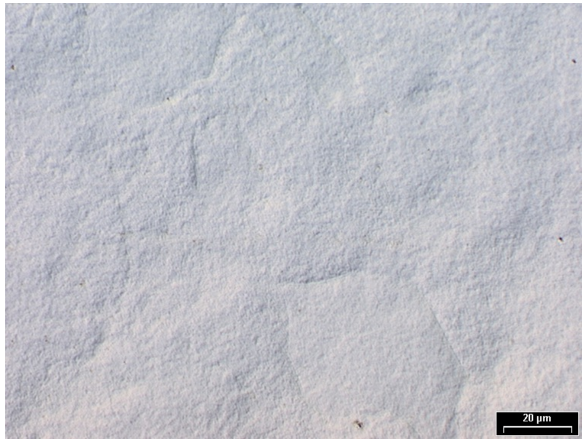


Main difference between BCP and EP: smoothening of grain boundaries.

After 120 µm of BCP



After120 µm of EP



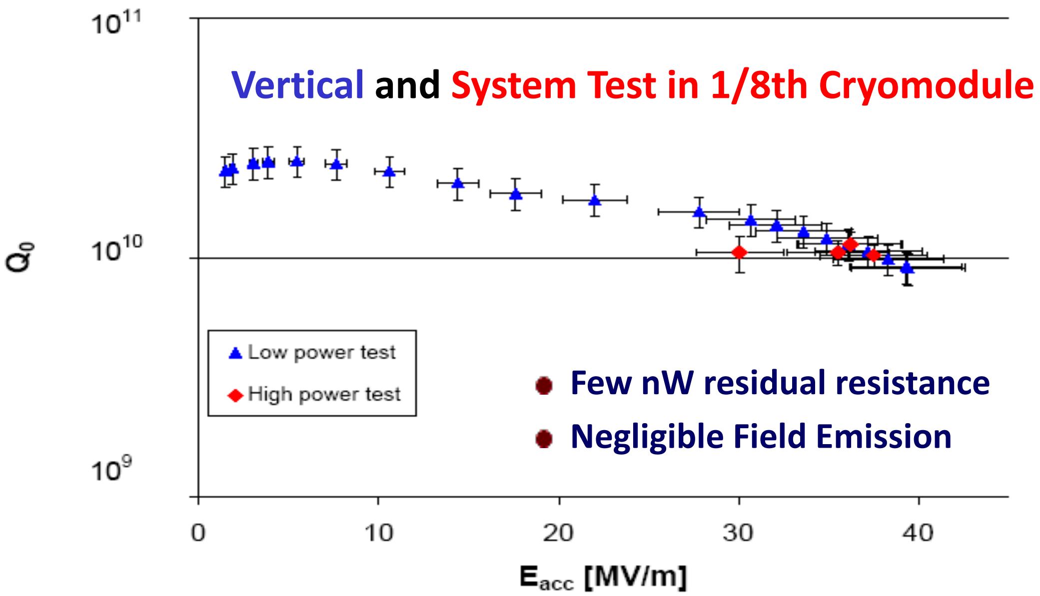
EP & Baking for 35 MV/m

EP at the DESY plant
• Low Field Emission

800°C annealing

120°C, 24 h, Baking
• high field Q drop cured

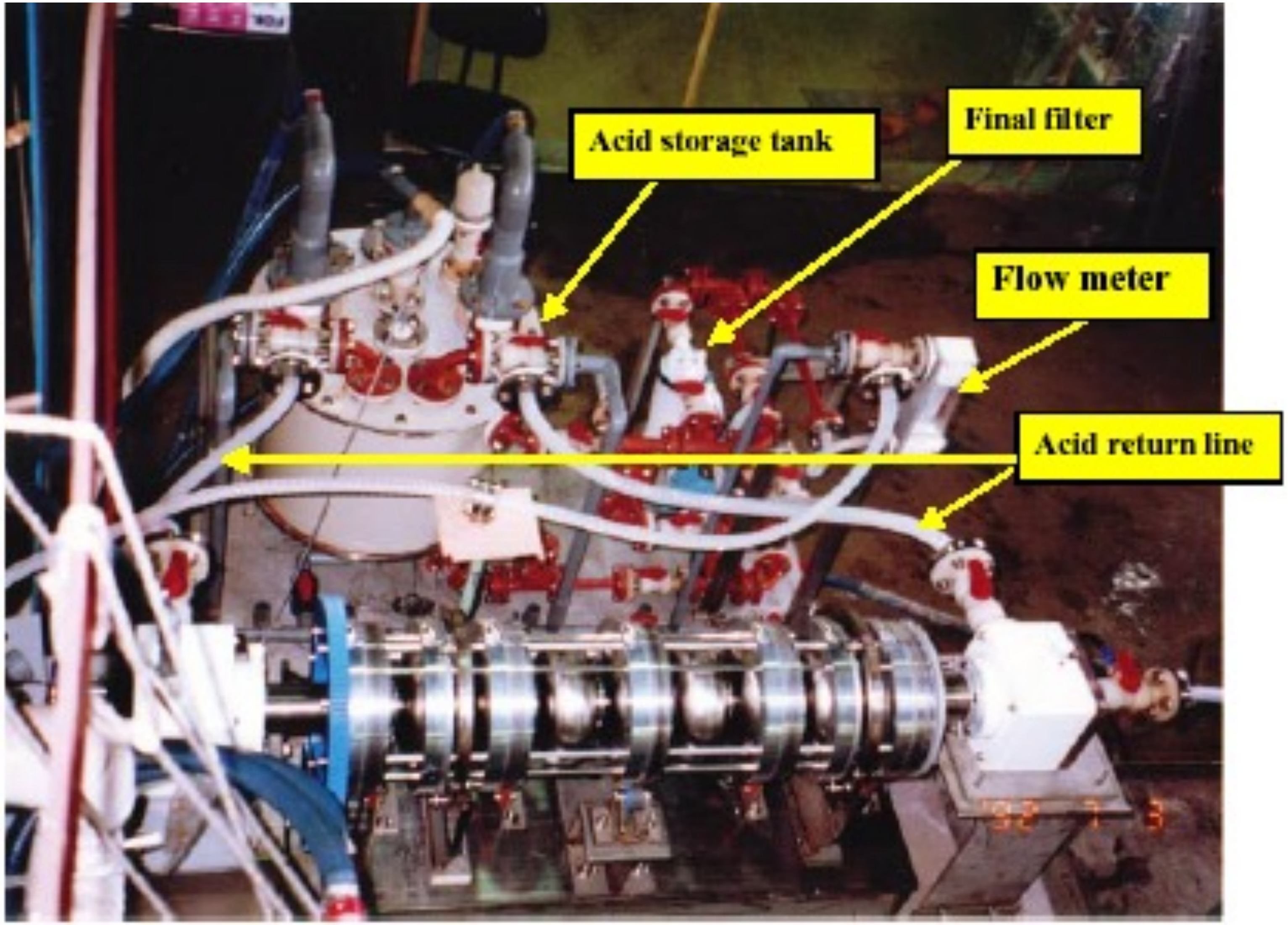
High Pressure Water Rinsing



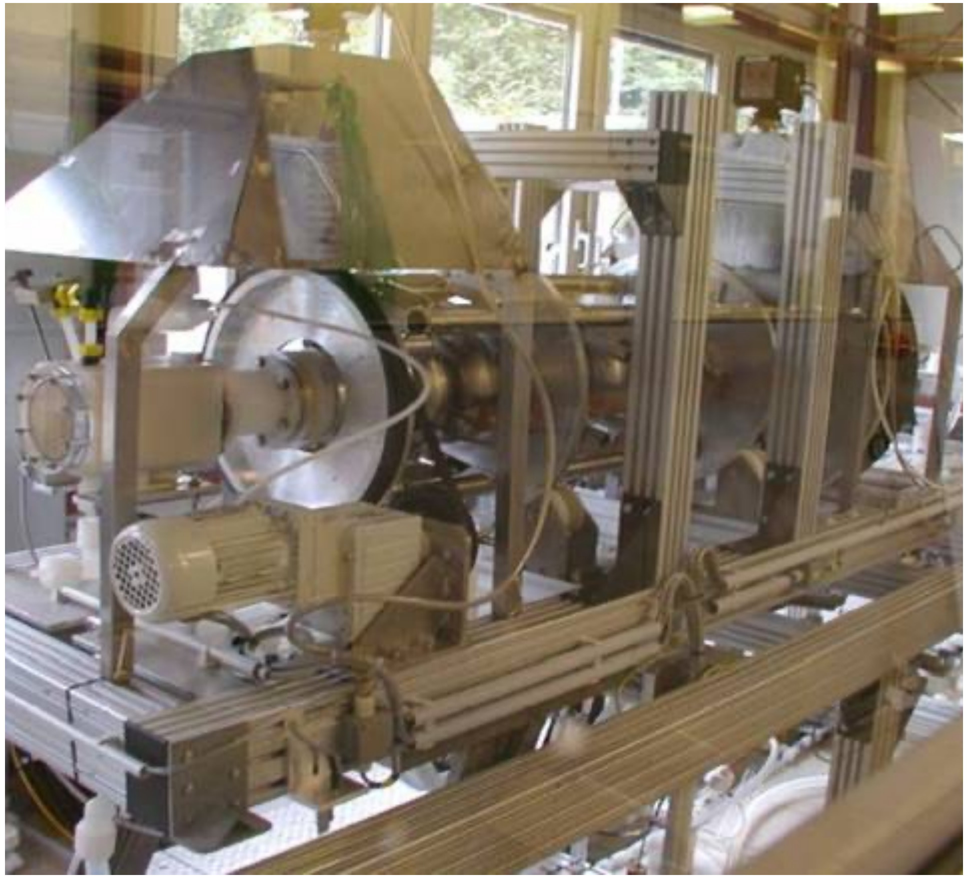
Electro-Polishing (EP)
instead of
Buffered Chemical Polishing (BCP)
• less local field enhancement
• High Pressure Rinsing more effective
• Field Emission onset at higher field

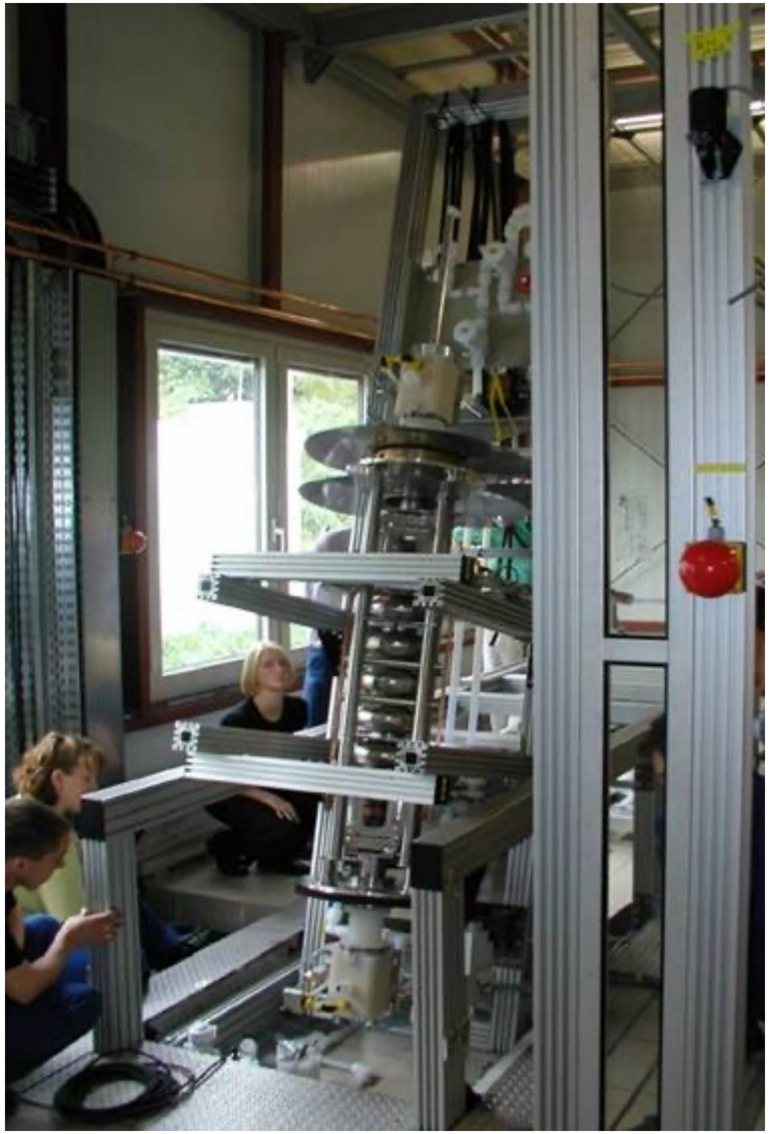
In Situ Baking
@ 120-140 ° C for 24-48 hours
• to re-distribute oxygen at the surface
• cures Q drop at high field

First Electro-Polishing @ Nomura (KEK)

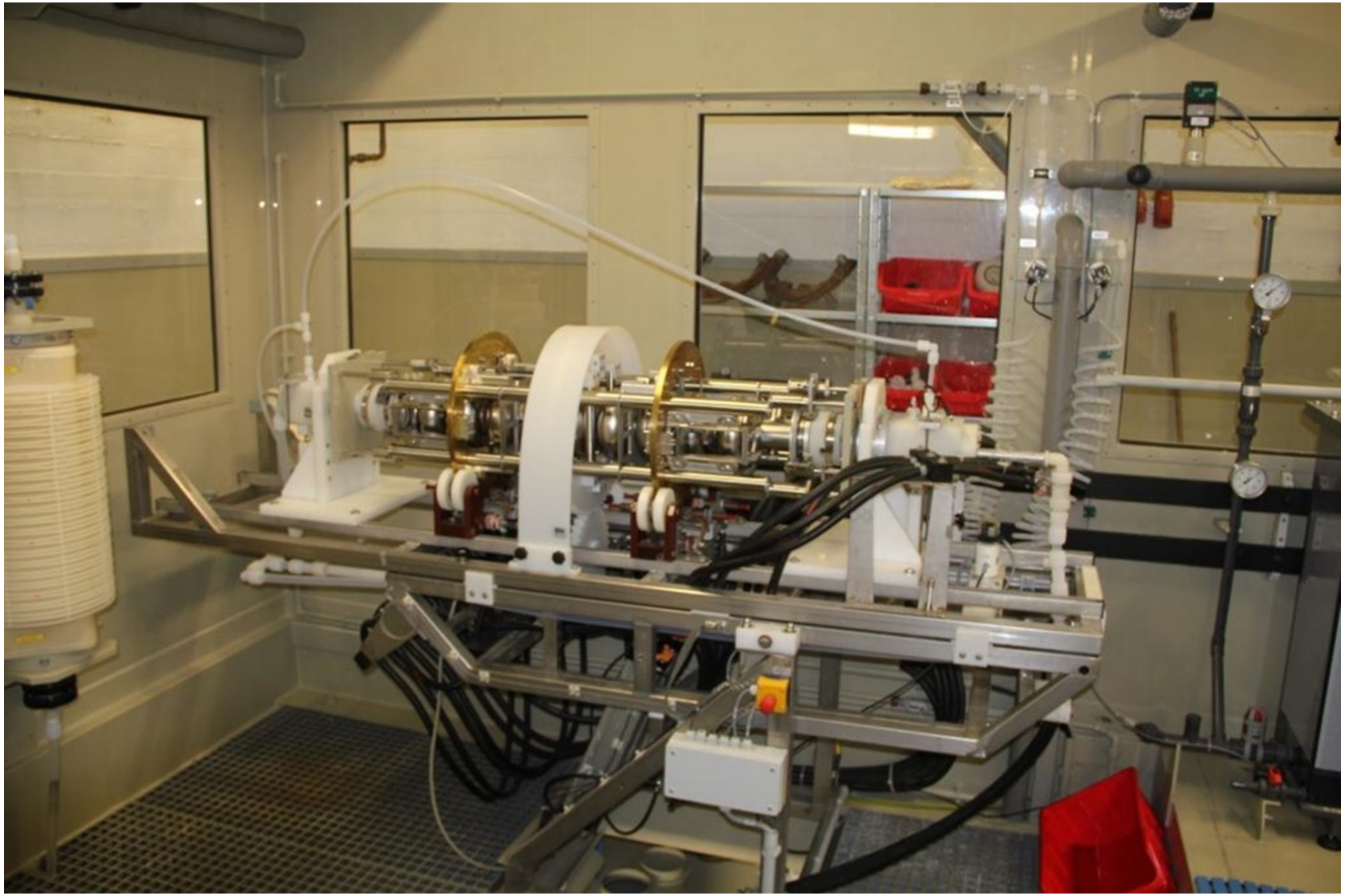


Reference EP System at DESY

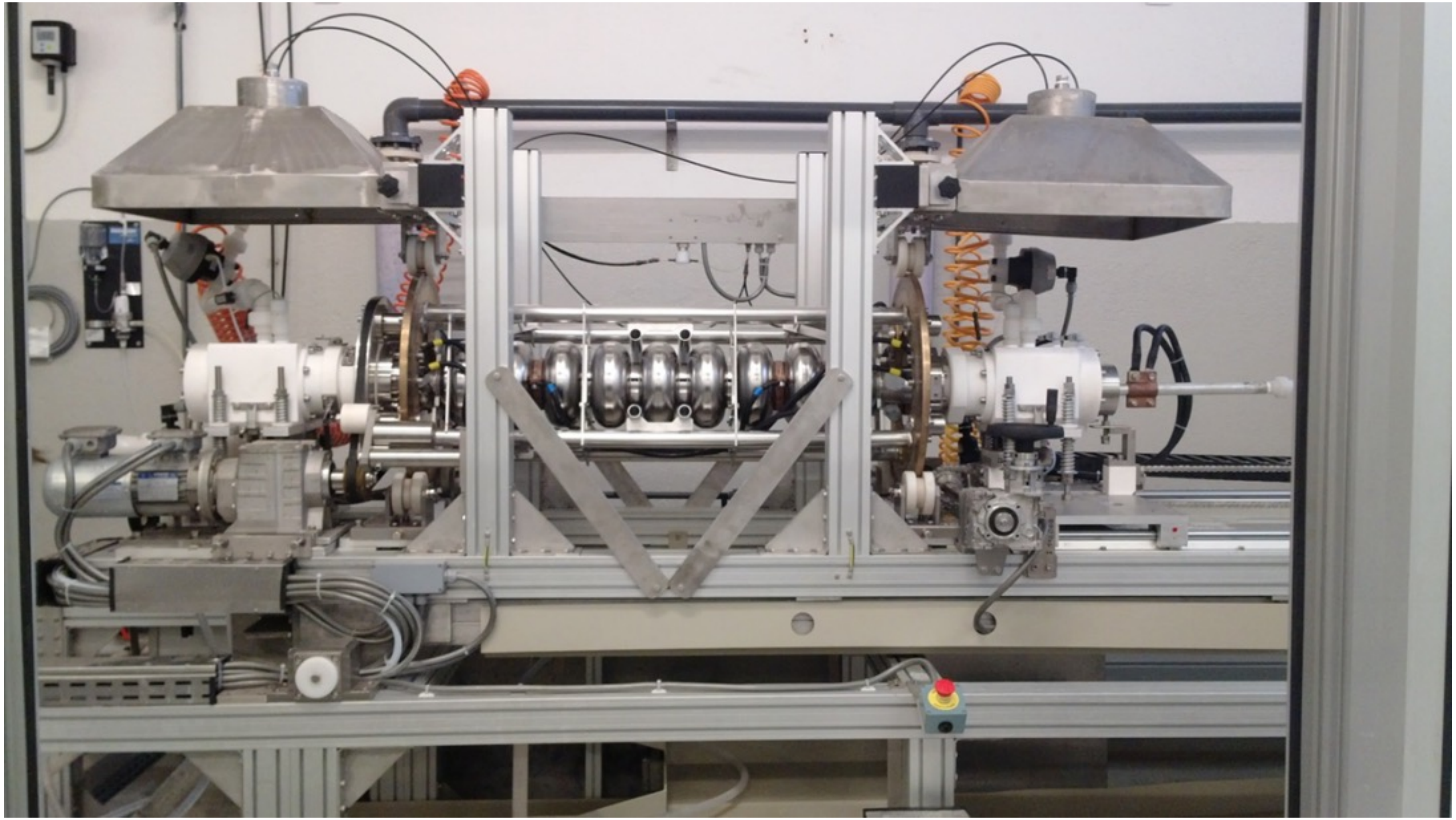




EP System in Industry (RI)

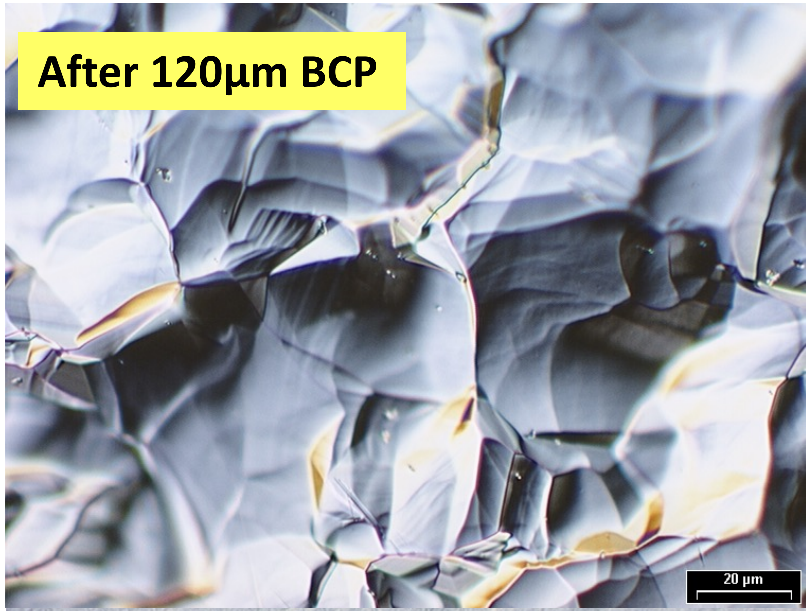


EP System in Industry (EZ)

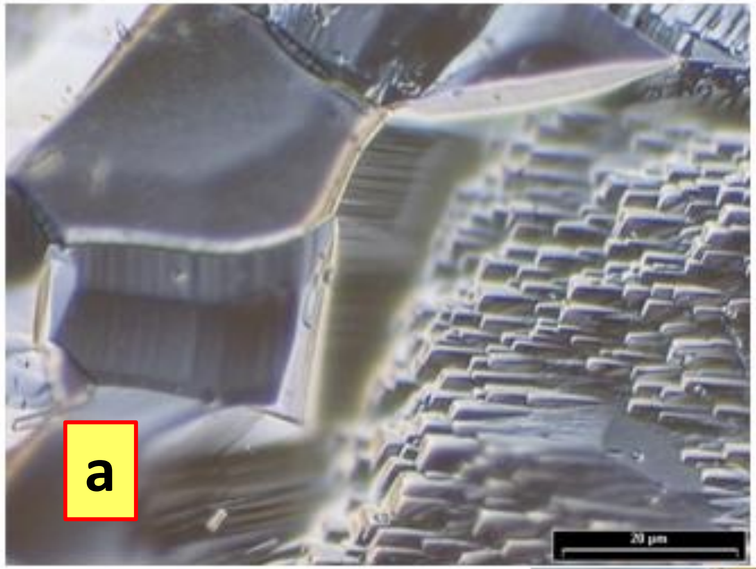


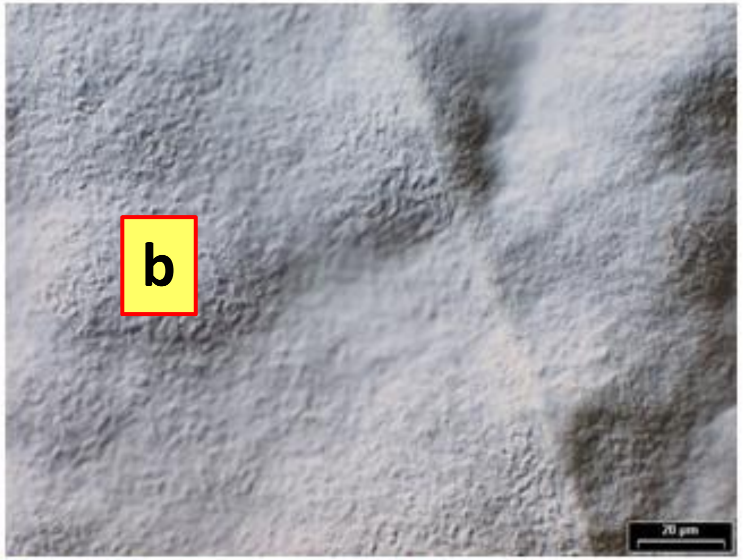
Comparison between BCP and EP

The main difference between BCP and EP is that of smoothening the grain boundaries

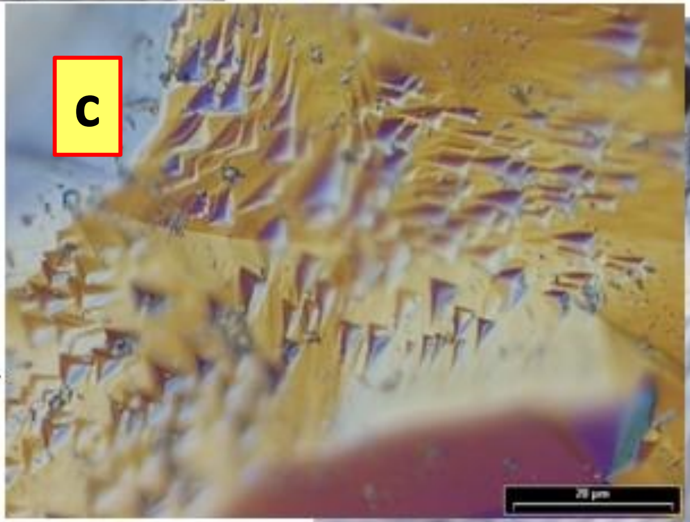


But life is much more complicate!!!



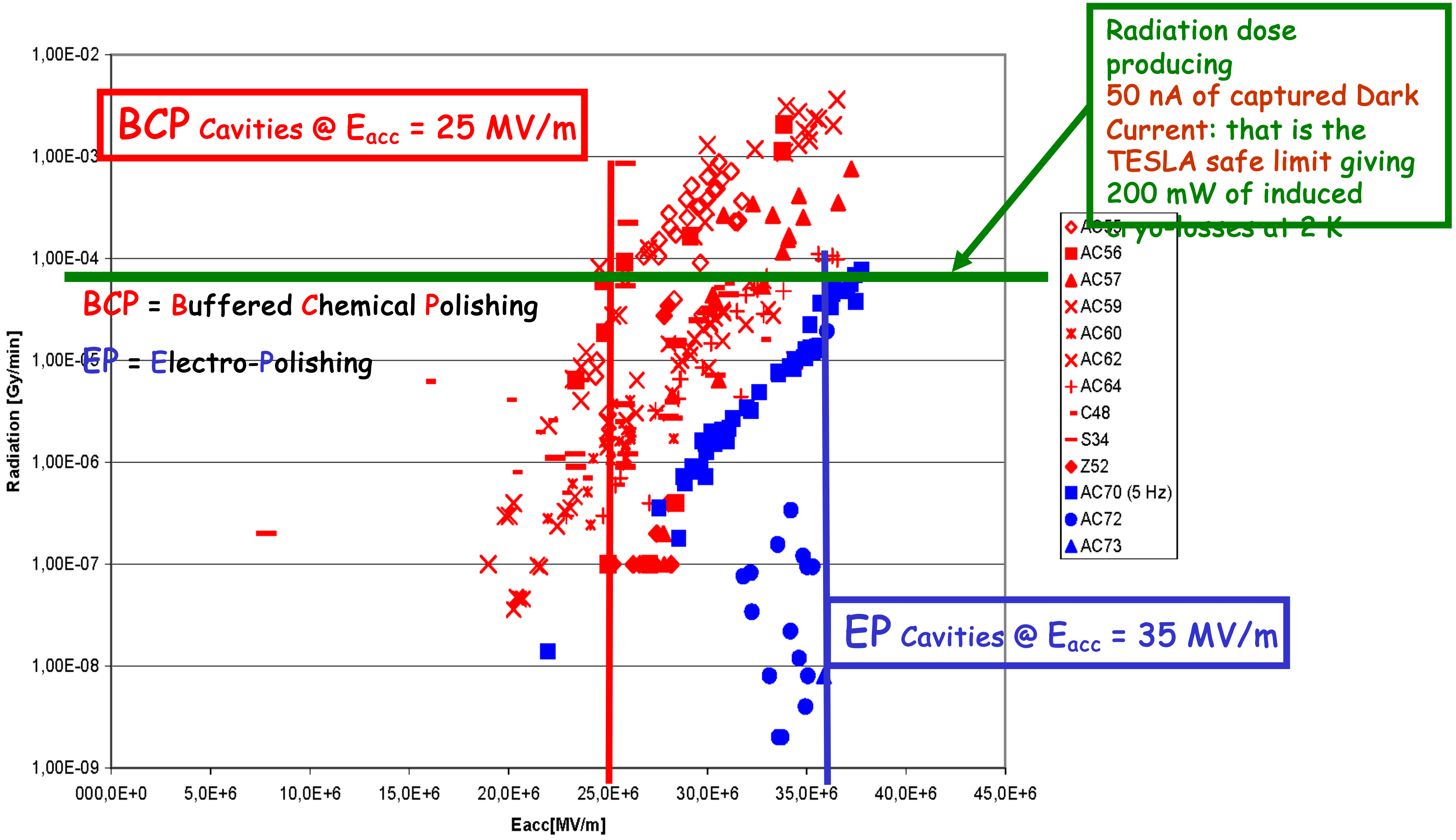


a) etching area
b) oscillation area
c) gas evolution area
d) dirty electrolyte



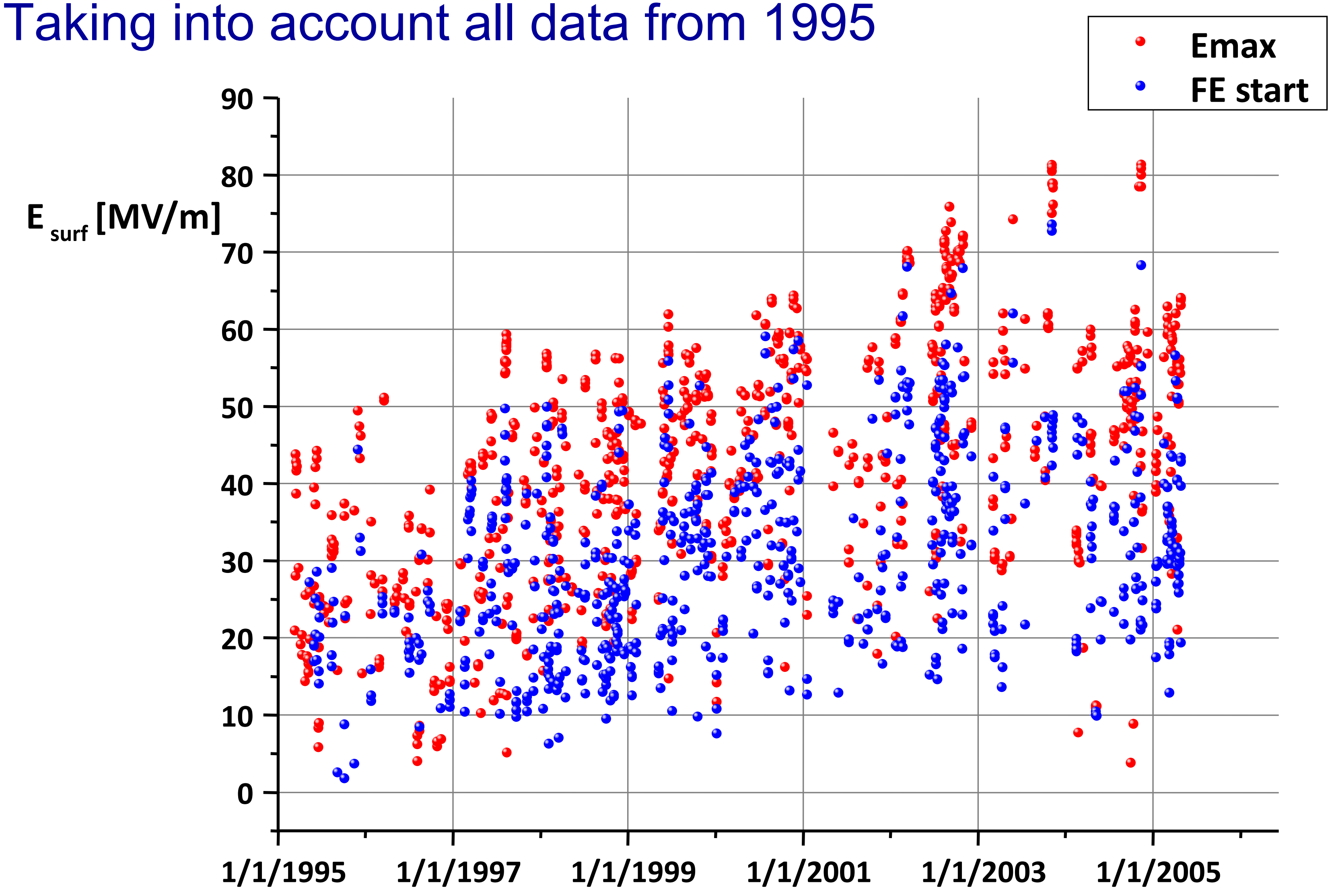
Field Emission pushed to higher field

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



TESLA Cavities: all tests to June '05

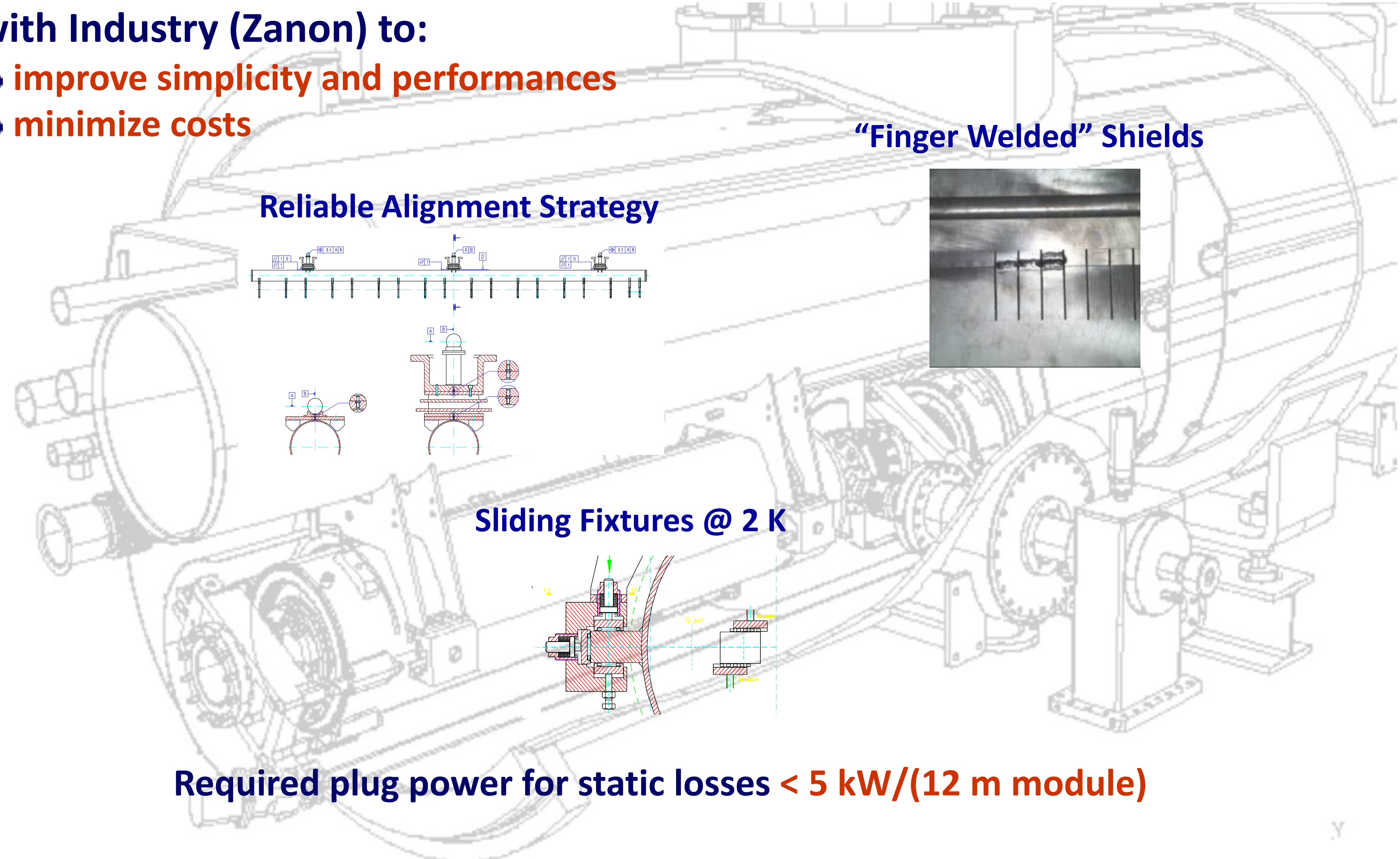
Taking into account all data from 1995



Cryomodule & Assembly as Crucial as Cavity

Three cryomodule generations developed by INFN in collaboration with Industry (Zanon) to:

- improve simplicity and performances
- minimize costs



"Finger Welded" Shields

Reliable Alignment Strategy

Sliding Fixtures @ 2 K

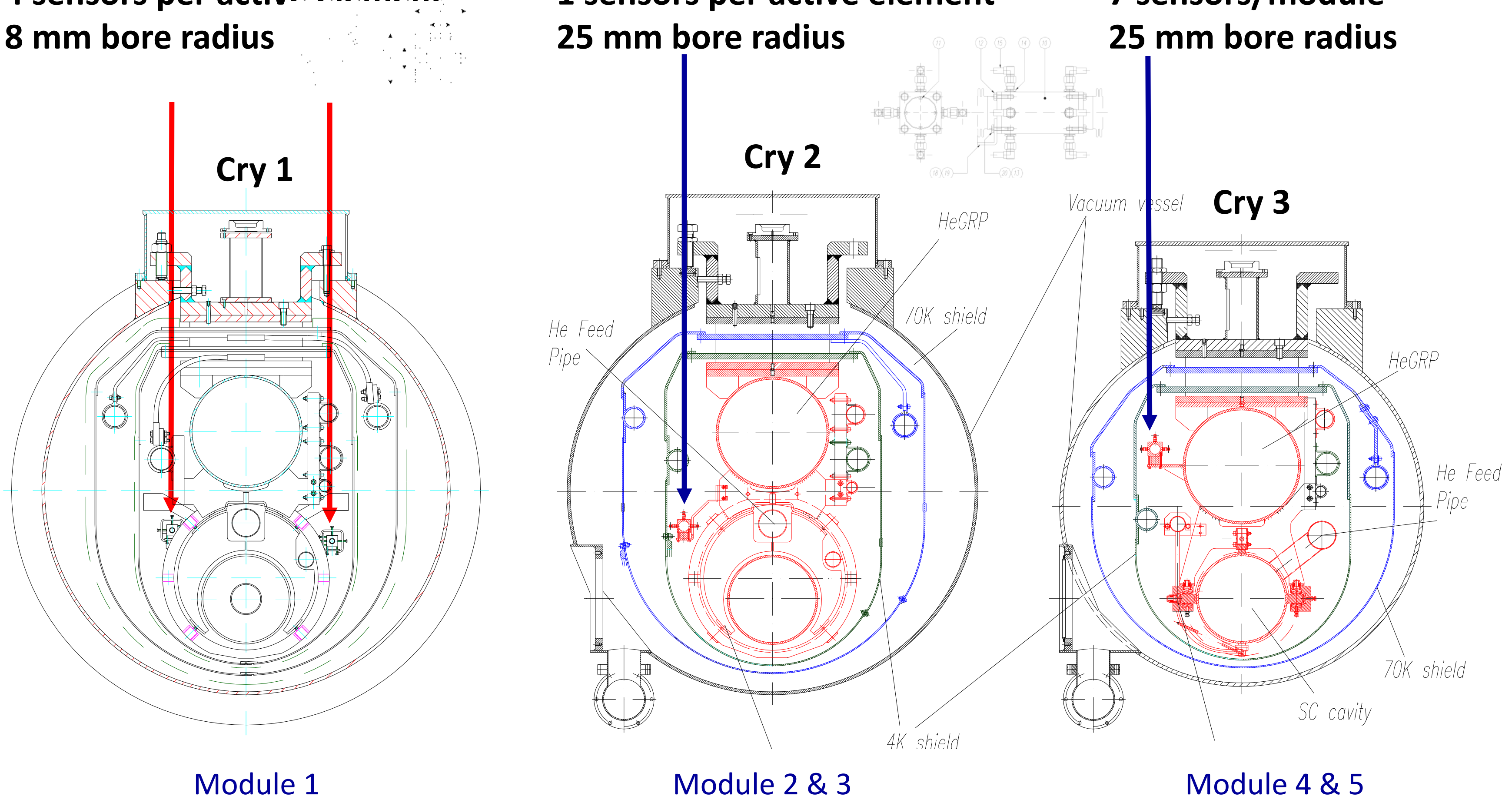
Required plug power for static losses < 5 kW/(12 m module)

Monitoring of cold mass movements during cool-down, warm-up and operation

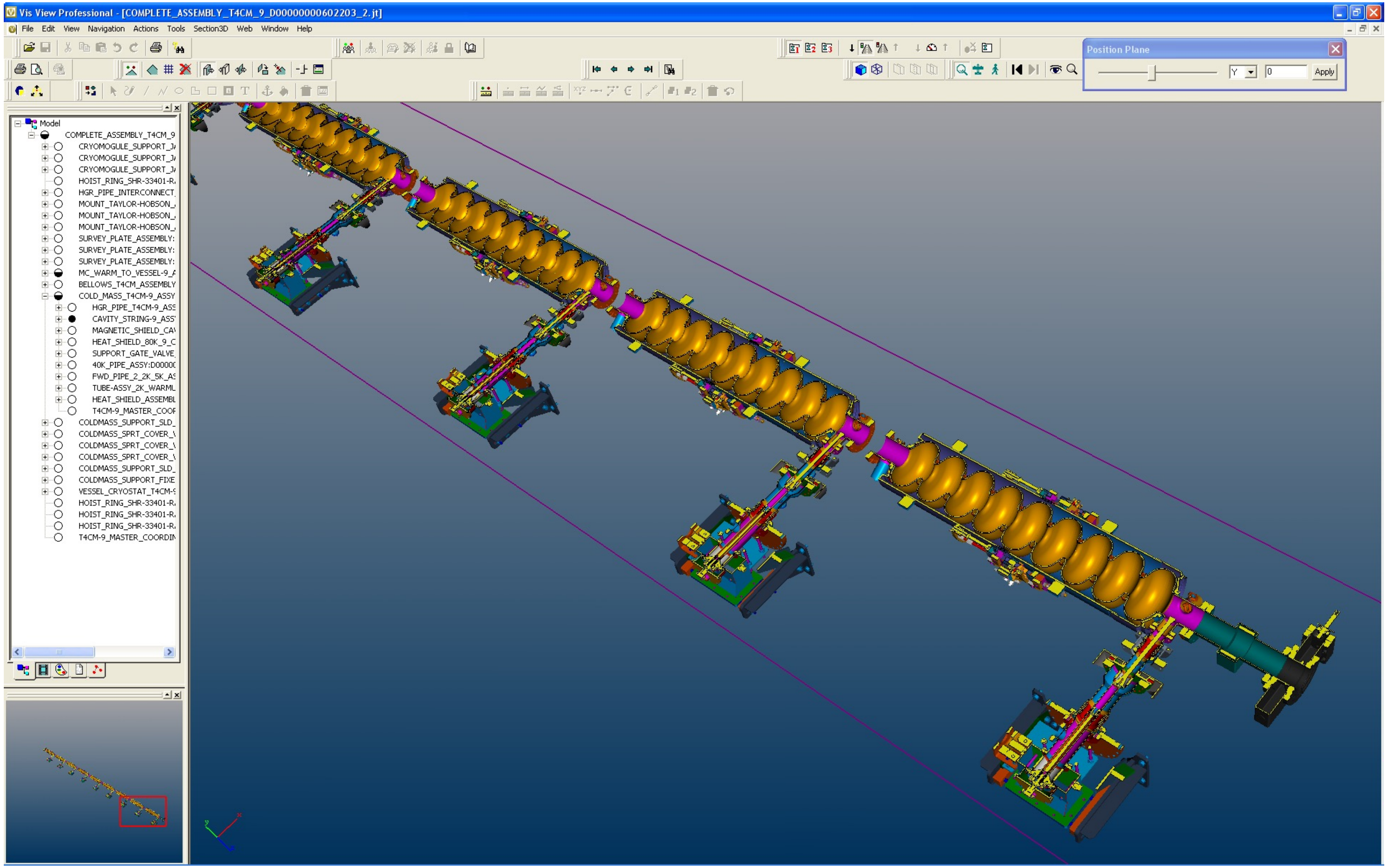
2 WPM lines with 2 x 18 sensors
4 sensors per active element
8 mm bore radius

1 WPM lines
1 sensors per active element
25 mm bore radius

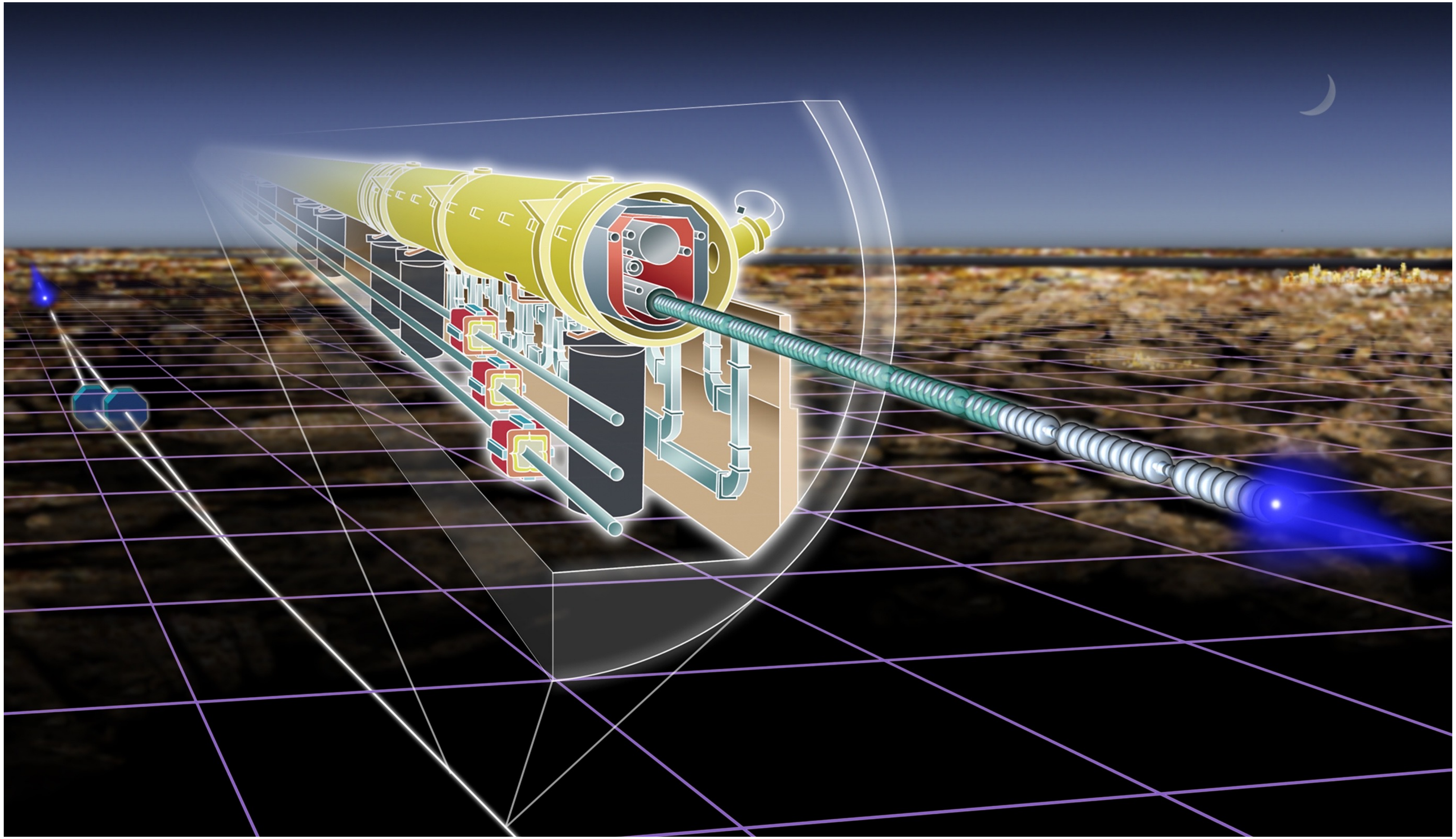
1 WPM line
7 sensors/module
25 mm bore radius



The INFN Cryomodule for XFEL & ILC

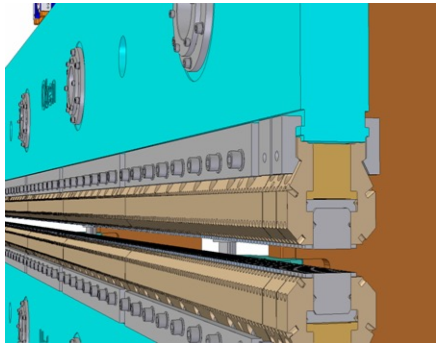


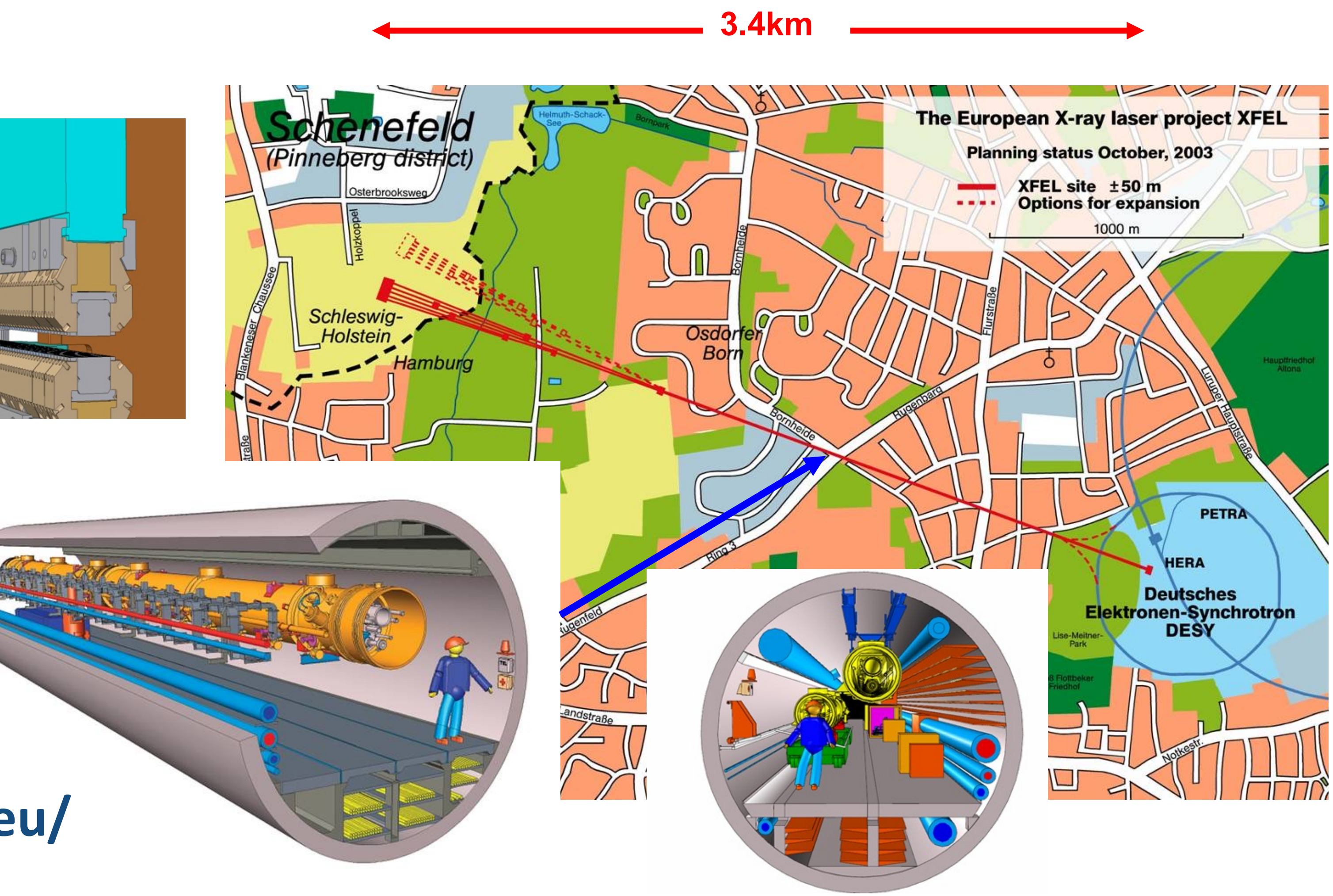
ILC: Pictorial View of the Winner



European XFEL: completed in 2016

https://www.youtube.com/watch?v=p3G90p4glQA





http://www.xfel.eu/

Thank you for your attention