9th European Particle Accelerator Conference

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Technical Issues for Large Accelerators based on High Gradient SC Cavities

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On leave from University of Milano

Introduction

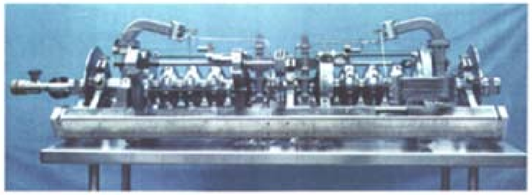
- Superconducting RF has been developed to efficiently transmit energy to a variety of particle beams
- For the first few decades the maximum usable accelerating field has been limited by the allowable technology in term of material production, cavity treatments and handling
- The construction and operation 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 **10^{10}**

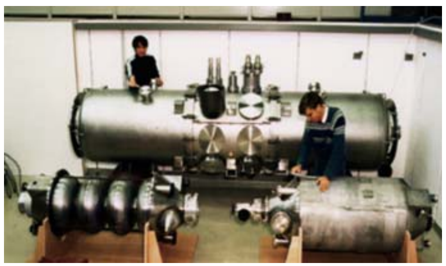
SRF before TESLA

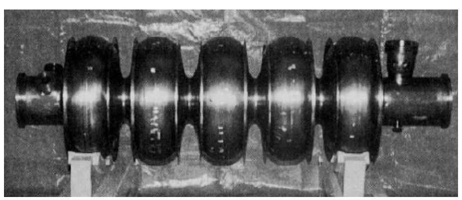
"Livingston Plot" from Hasan Padamnee

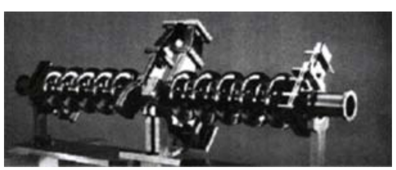
Total Installation > 1000 m

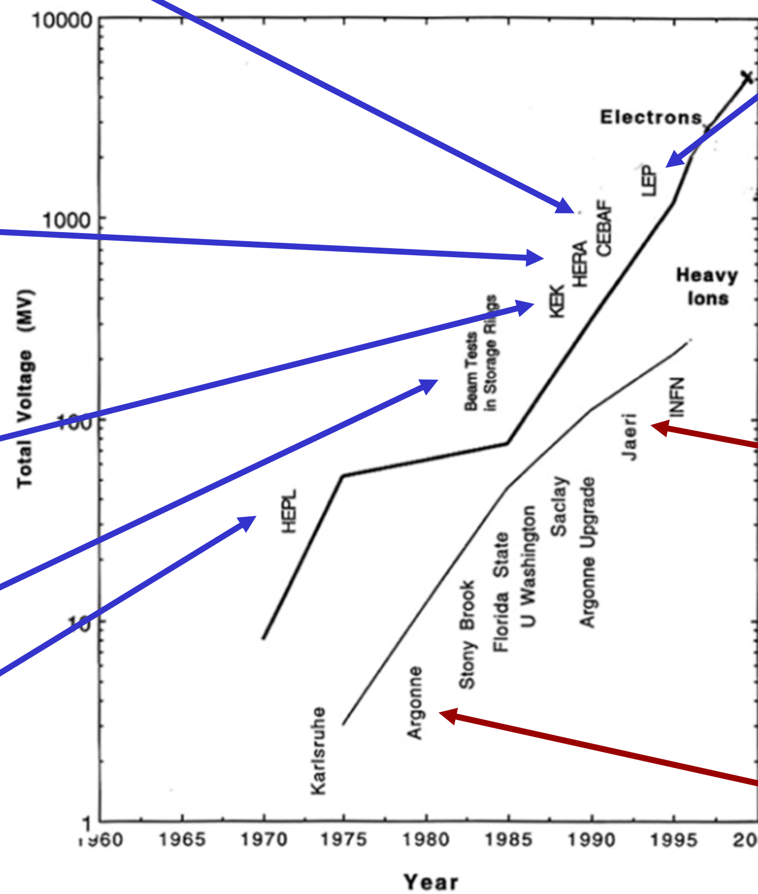
Provided > 5 GV

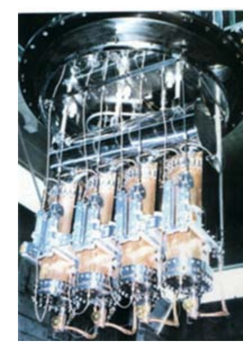










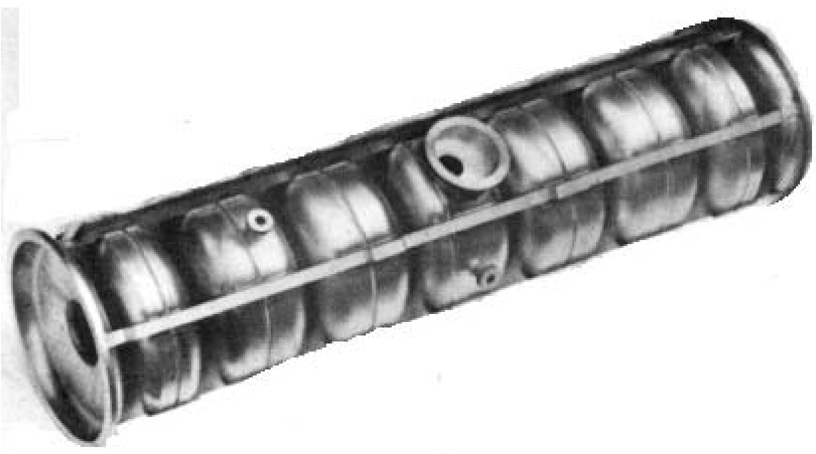


From the pioneering age to 1984

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

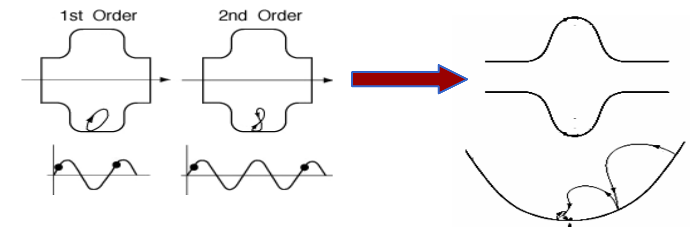
Field Emission

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

R&D waiting for big projects

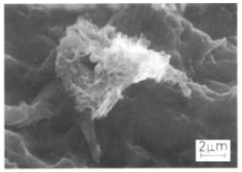
Multipactoring

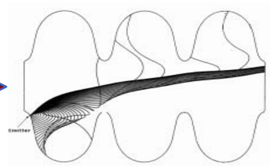
- A few computer codes developed
- Spherical shape realized at Genova and qualified at Cornell & Wuppertal



Field Emission

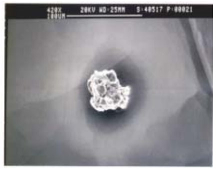
- Emitters were localized and analyzed
- Improved treatments and cleanness

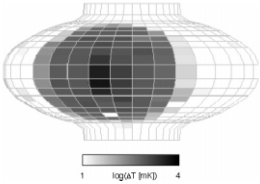




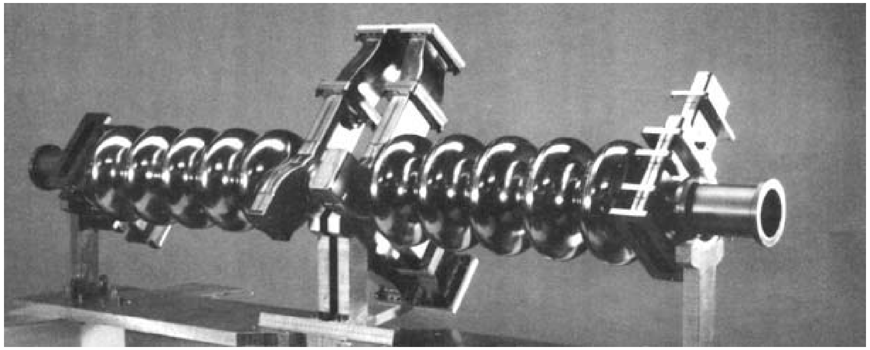
Quenches/Thermal Breakdown

- Higher RRR Nb
- Deeper control for inclusions





E_{acc} > 5 MV/m



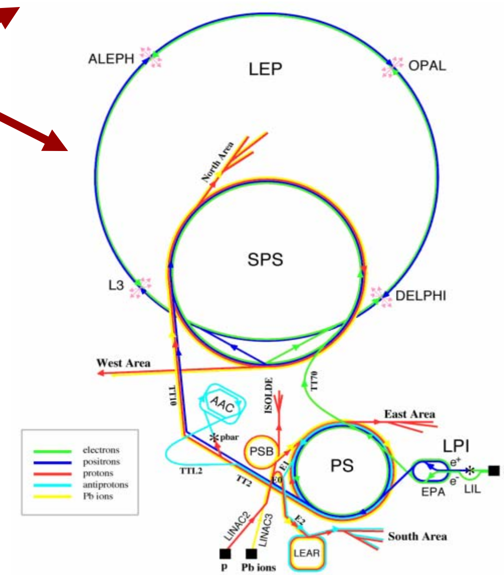
1984/85: First great success

- 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 midle '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

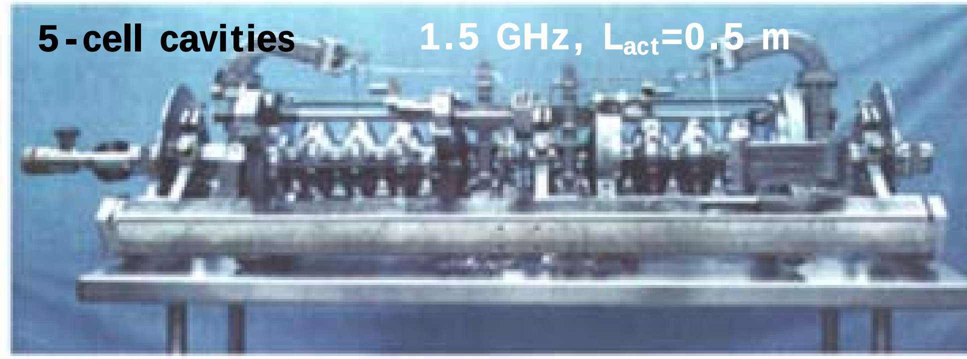
- In 1985 the successful test of a pair of SC cavities in CERS opened the door to the large scale application of SRF for electrons
- The decision of applying this unusual technology in the largest HEP accelerators forced the labs to invest in Research & Development, infrastructures and quality control
- 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

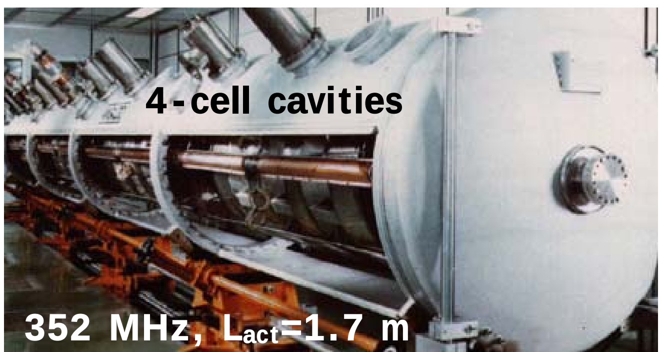
CEBAF and LEP II

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

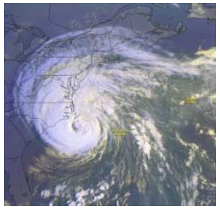
Maximum energy and beam current above the design values

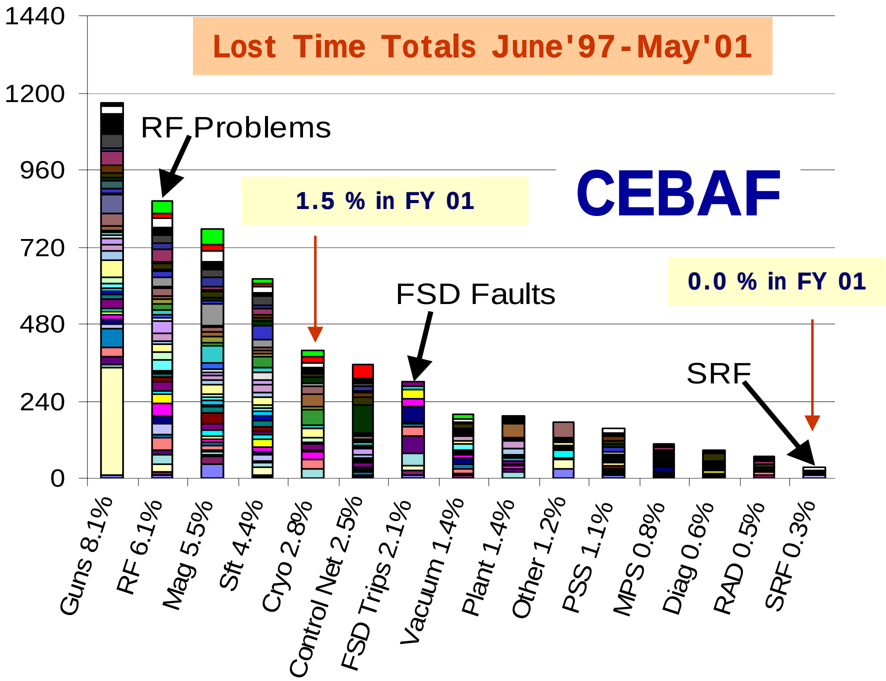
CEBAF performances finally limited by the installed cryo-power and RF-power

Excellent reliability of SRF technology

High availability for physics

The only warm-up for
Isabelle Hurricane



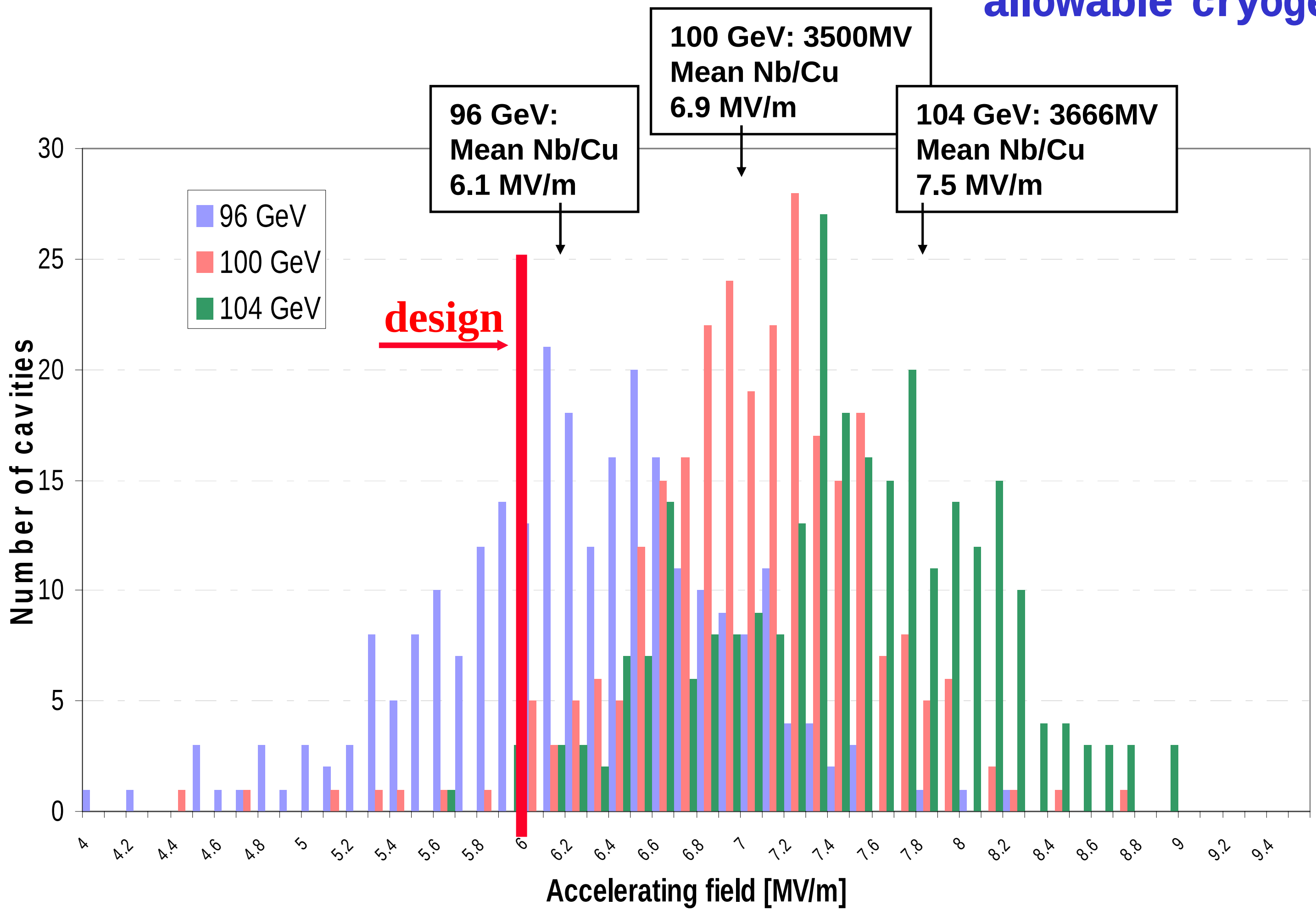


A great success for LEP II

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 Mission

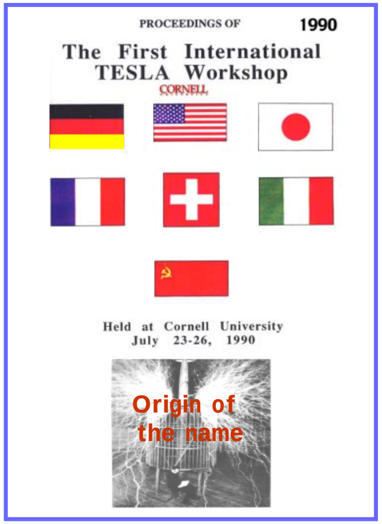
Develop SRF for the future TeV Linear Collider

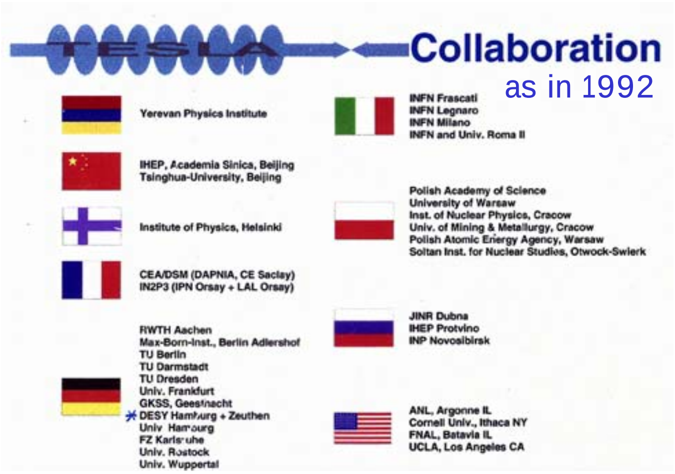
Basic goals:

- **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

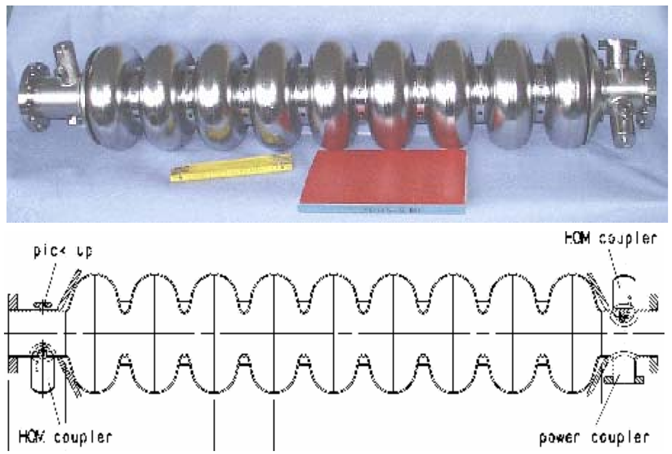




TESLA cavity design and rules

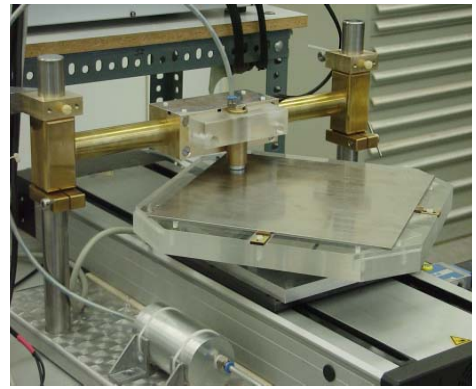
Major contributions from: CERN, Cornell, DESY, CEA-Saclay

- **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

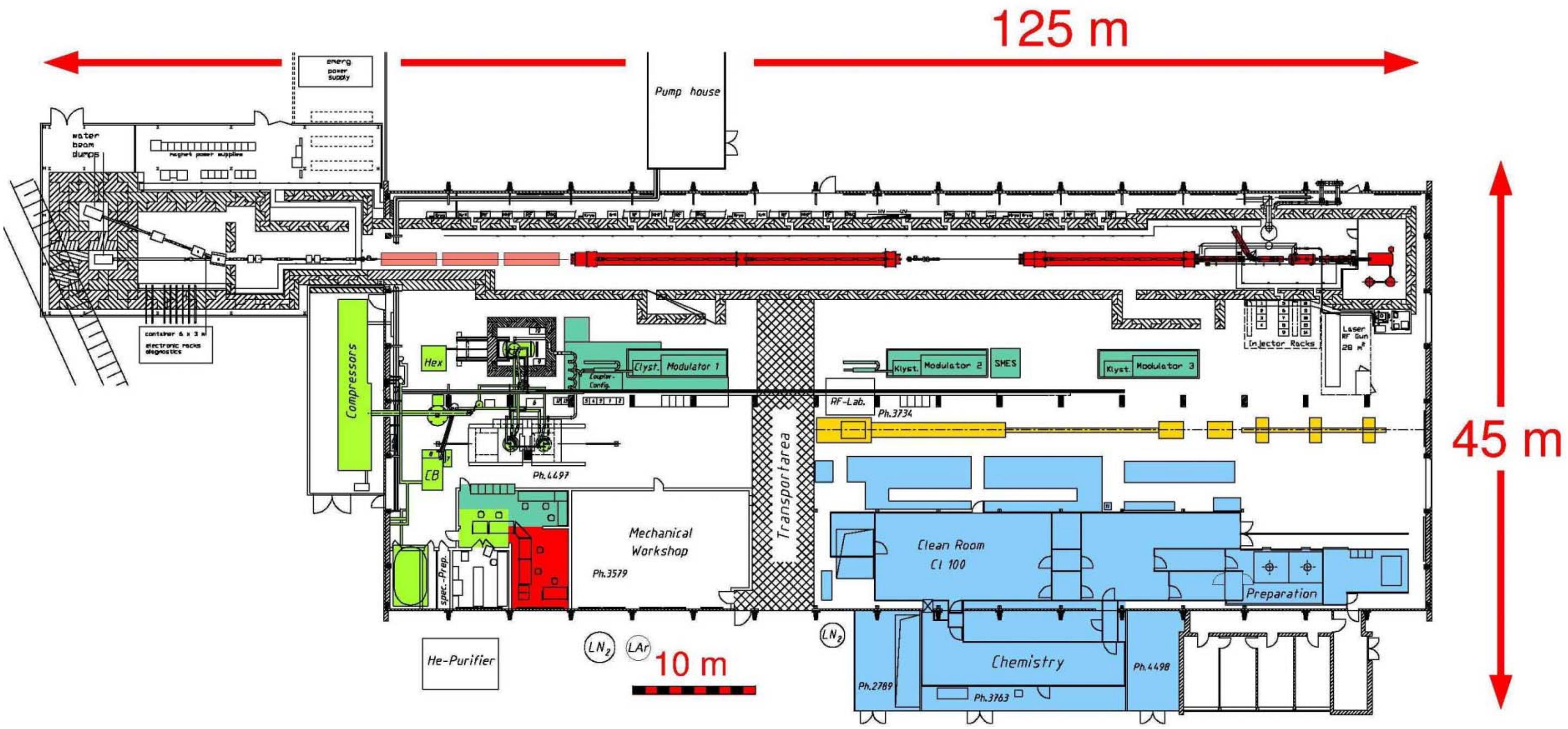

Cleanroom handling of niobium cavities

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

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)



BCP preparation of TESLA Cavities

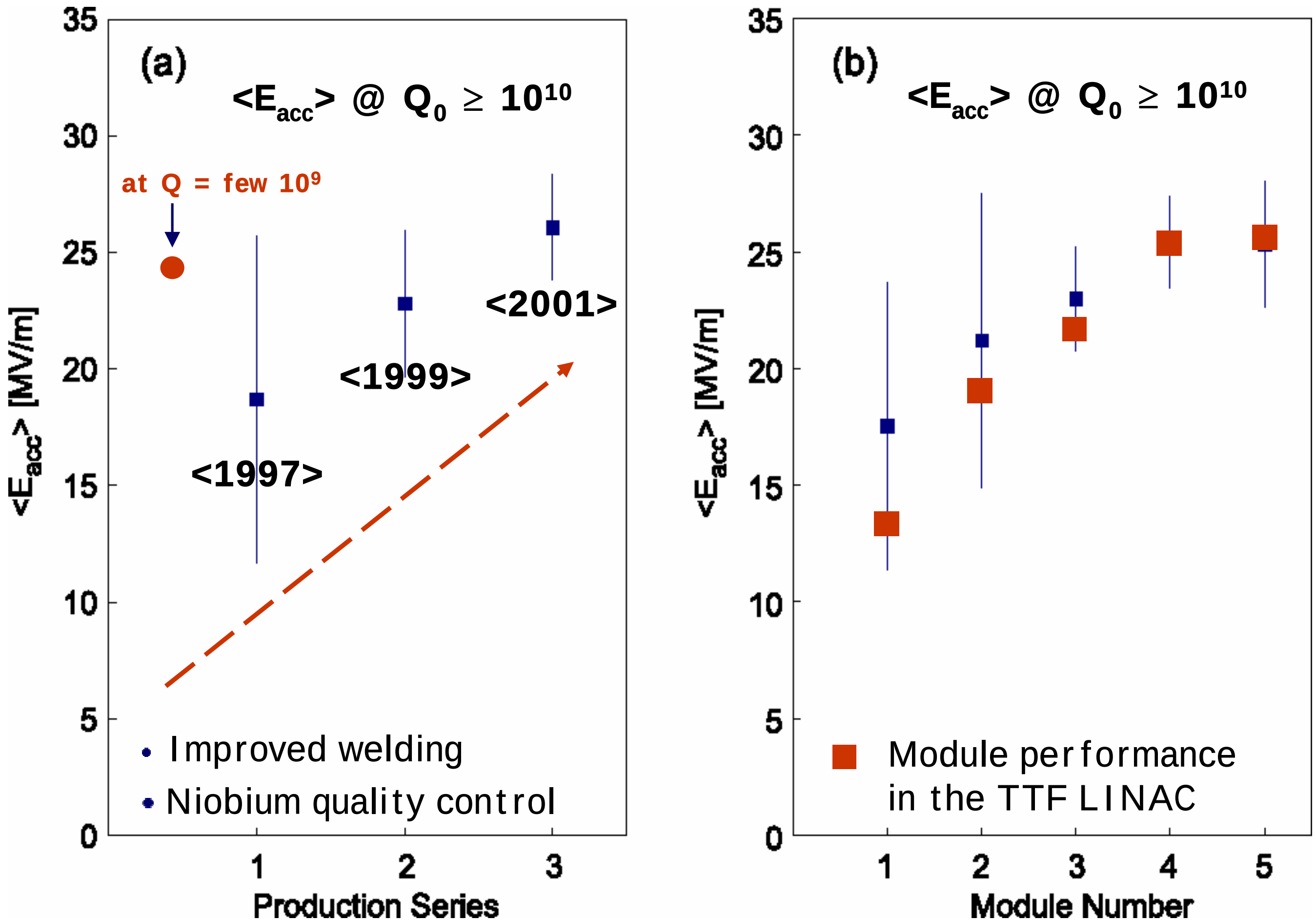
Learning curve with BCP

BCP = Buffered Chemical Polishing

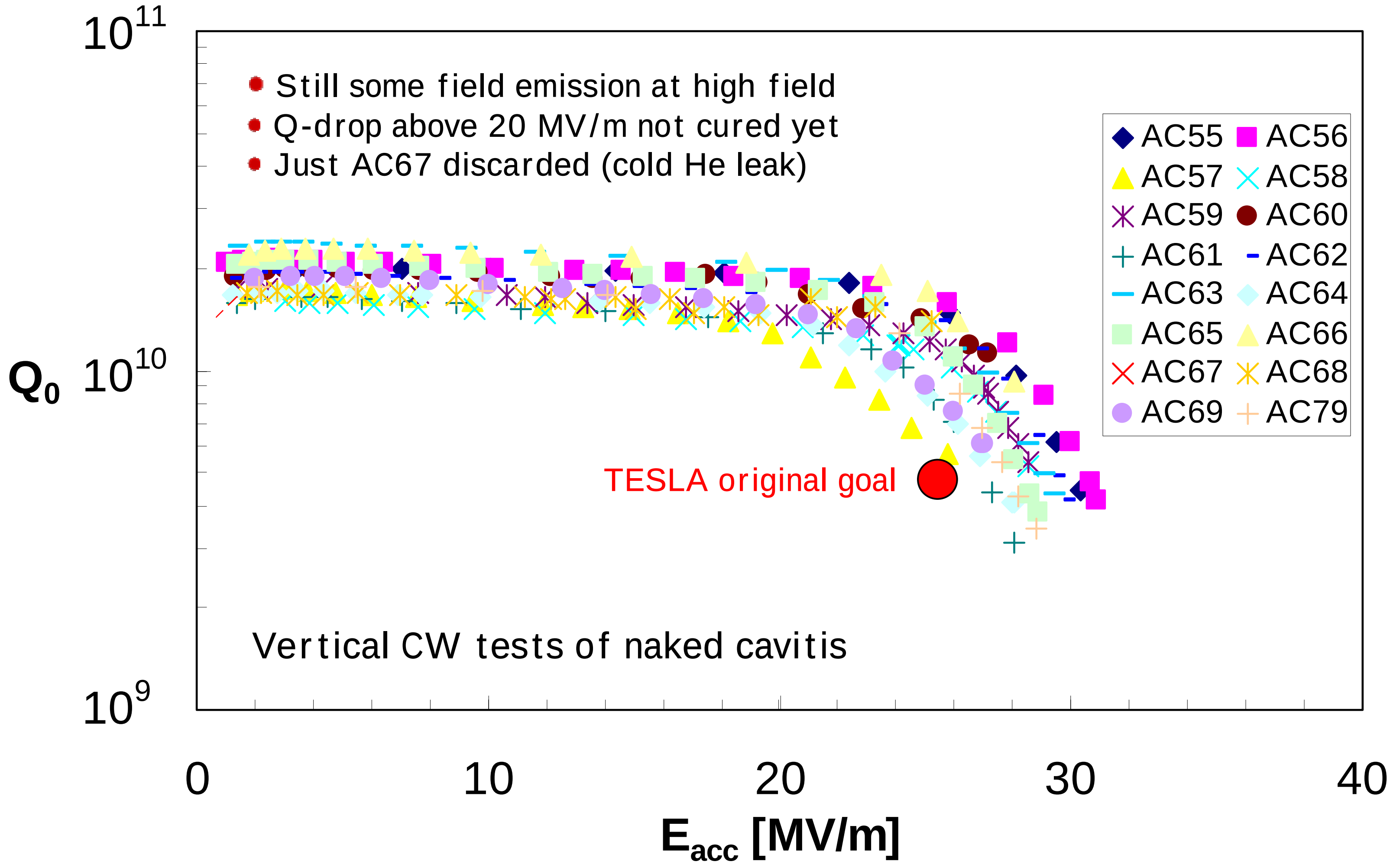
3 cavity productions from 4 European industries: Accel, Cerca, Dornier, Zanon

Cornell 1995 ●

5-cell



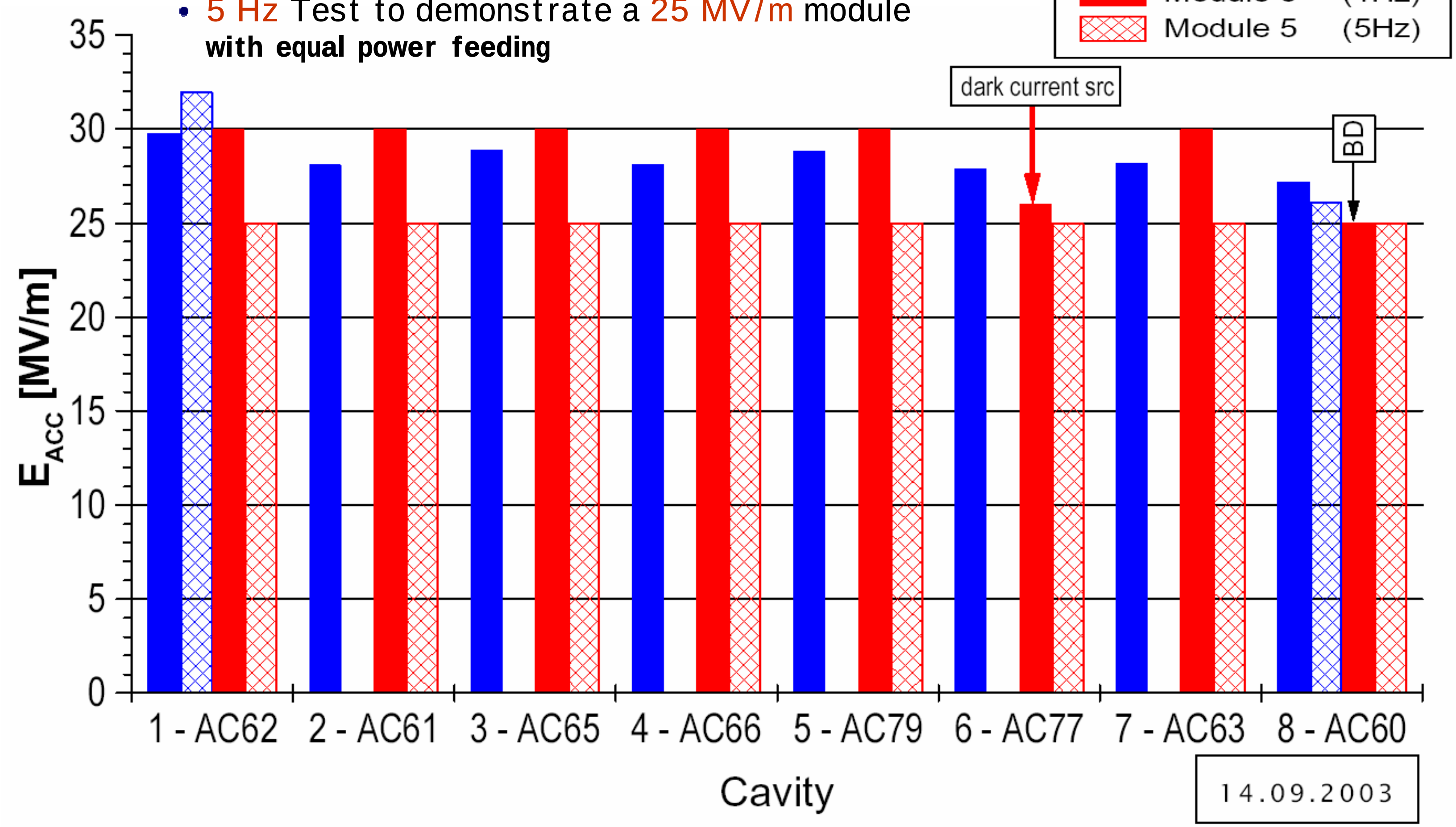
3rd cavity production with BCP



RF performances in module # 5

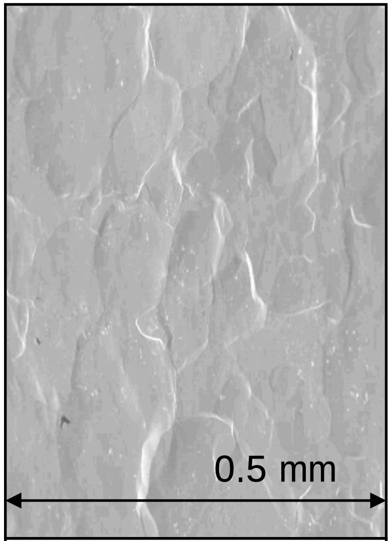
Status of Art for BCP Cavities

- 6 cavities exceed 30 MV/m (single cavity test)
- 1 cavity shows field emission at high field
- 1 cavity is quenching at 25 MV/m
- 5 Hz Test to demonstrate a 25 MV/m module **with equal power feeding**

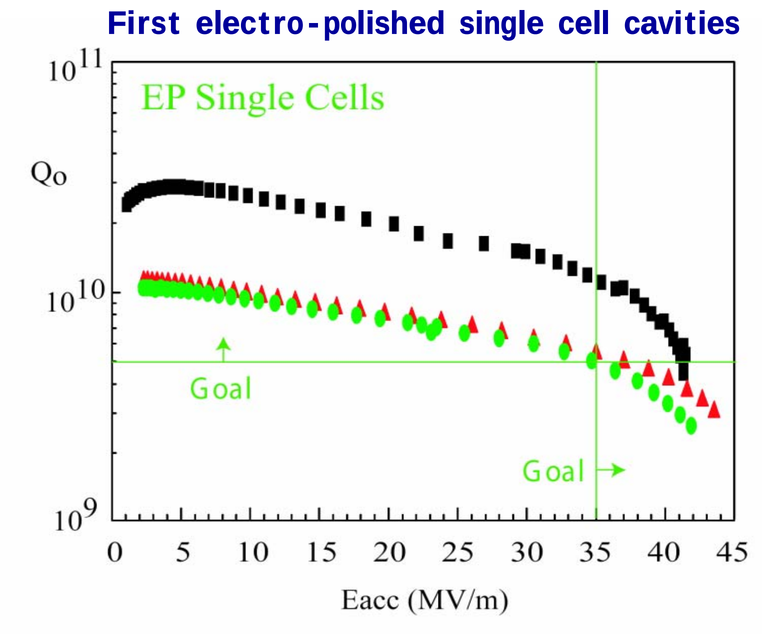


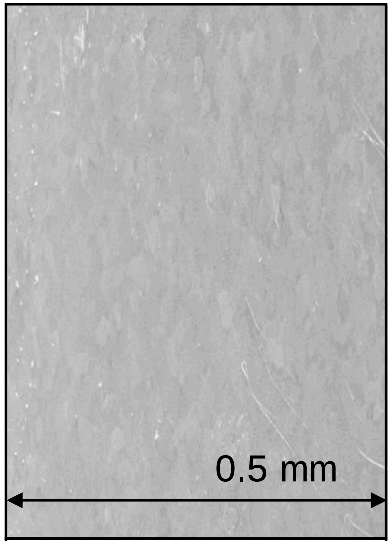
Electro-Polishing for 35 MV/m

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



BCP Surface
(1μm roughness)





EP Surface
(0.1μm roughness)

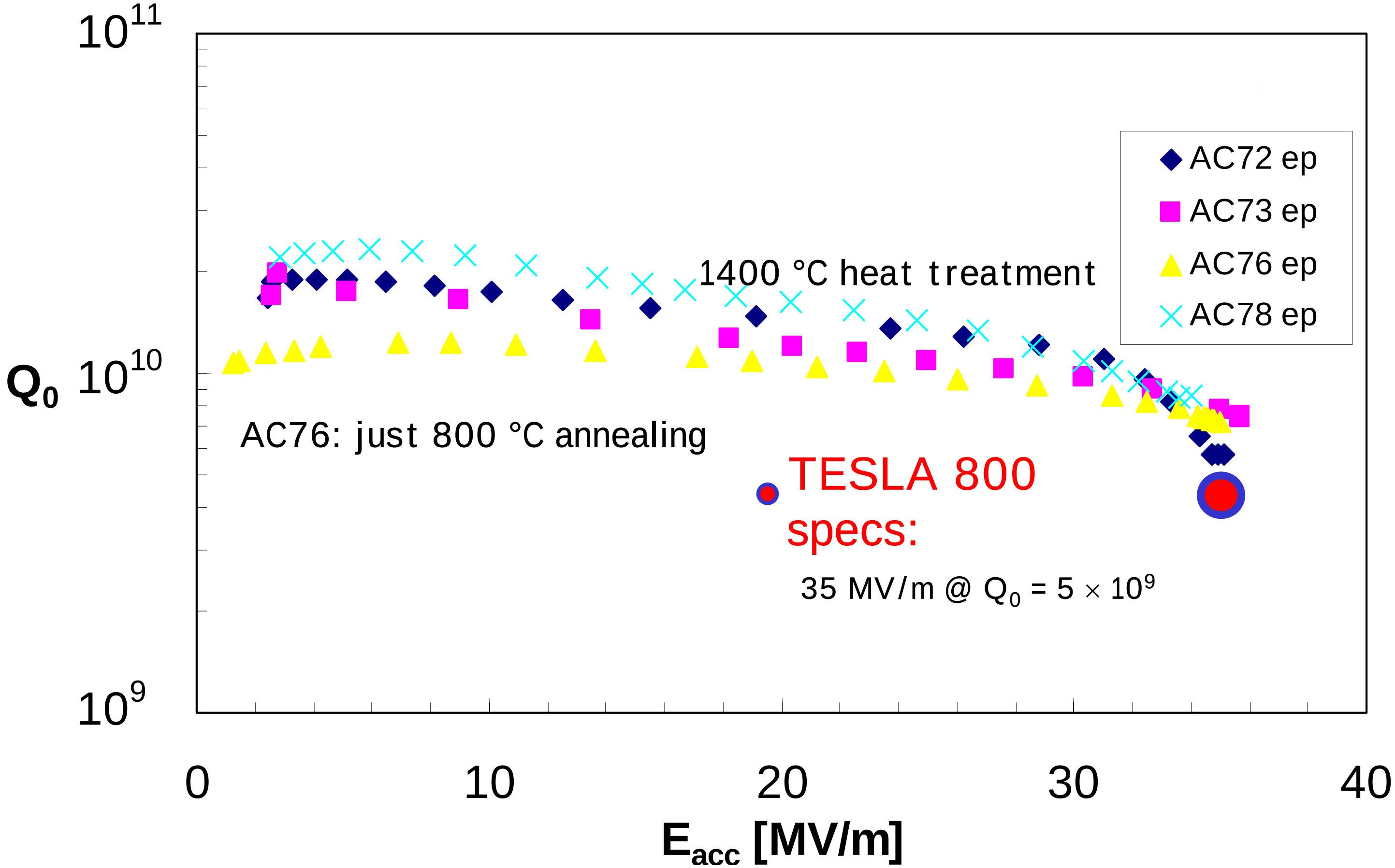
Electro-polishing (EP) instead of the Buffered Chemical Polishing (BCP)

- 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)

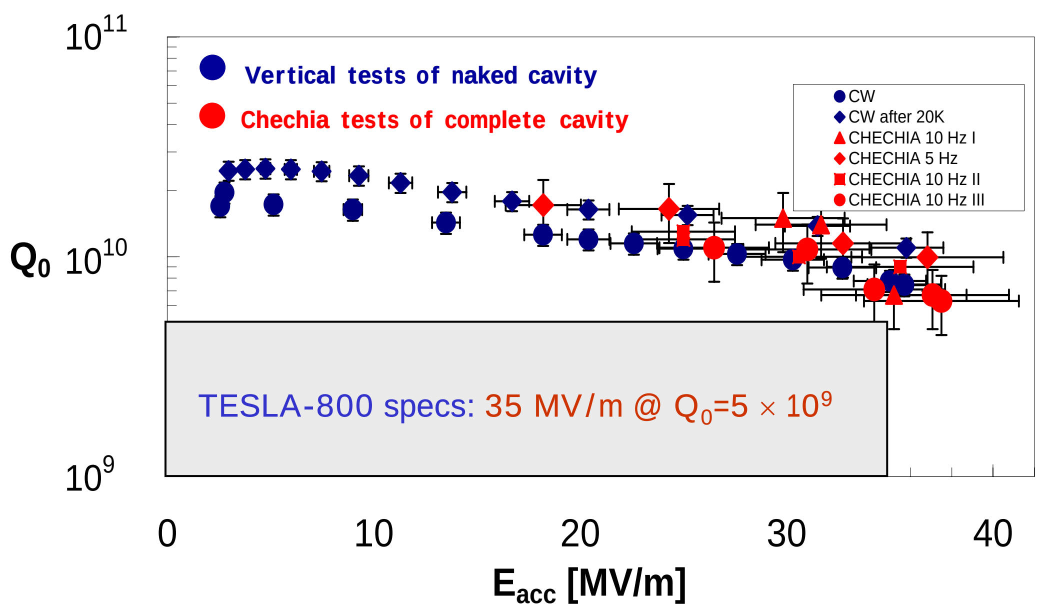
1100 hr continuous operation at 35MV/m

No ‘faults’ observed

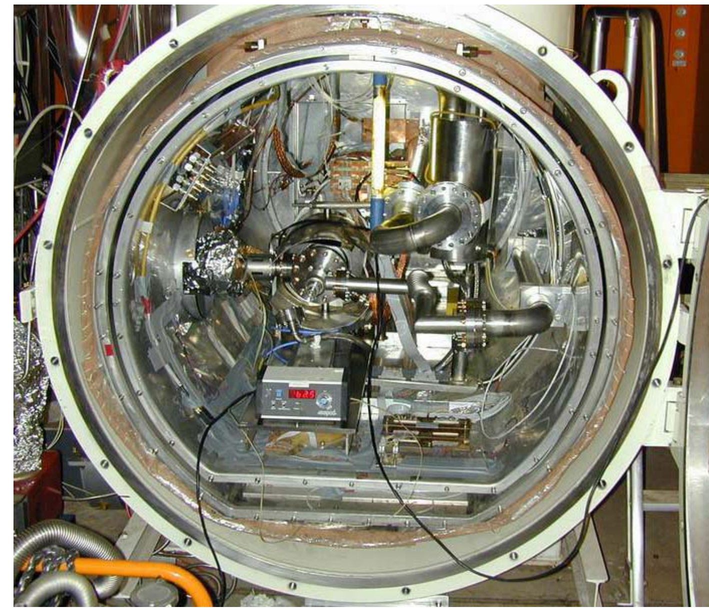
- due to couplers
- nor due to cavities

Forced ‘trips’ caused no damage to cavity/coupler

- No degradation observed
- Some improvement due to natural processing



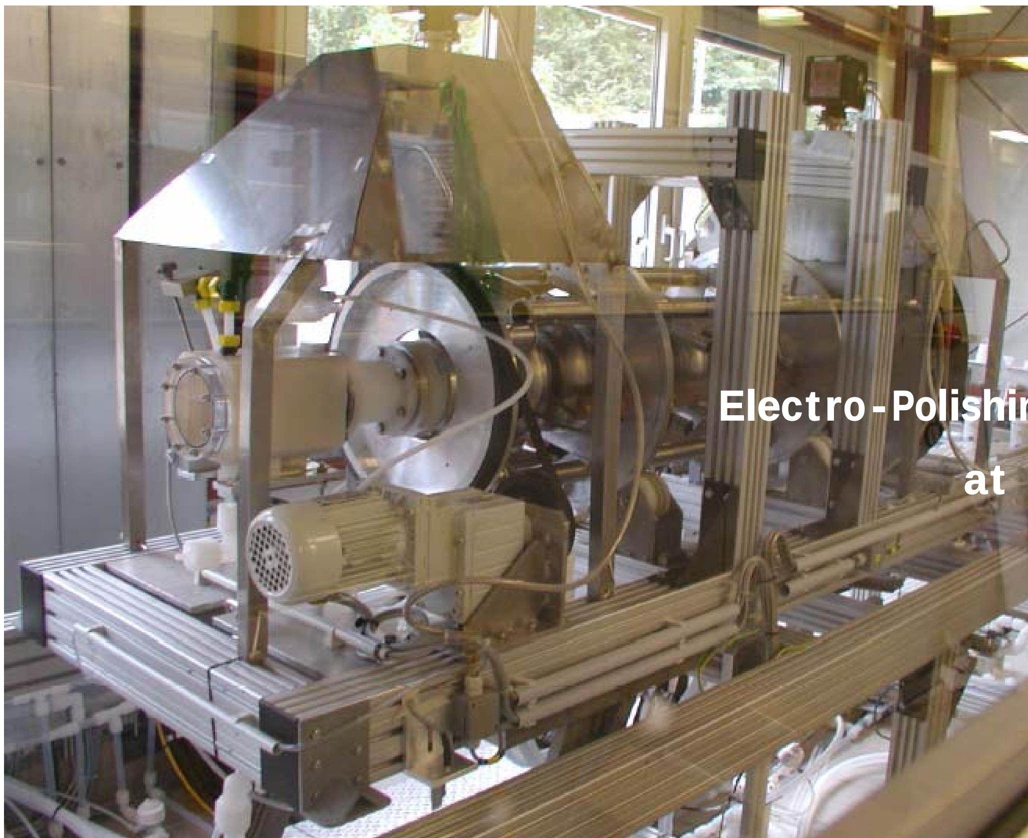
The Horizontal Cryomodule “CHECHIA”



- 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

EP + Backing played the crucial role

- **Q drop** at high field **cured** by 120 °C backing
- Better HPR surface cleaning (smoother surface) pushed to **onset of FE > 10 MV/m higher**




Electro-Polishing Infrastructure at DESY

AC70: Processed in the DESY EP Plant

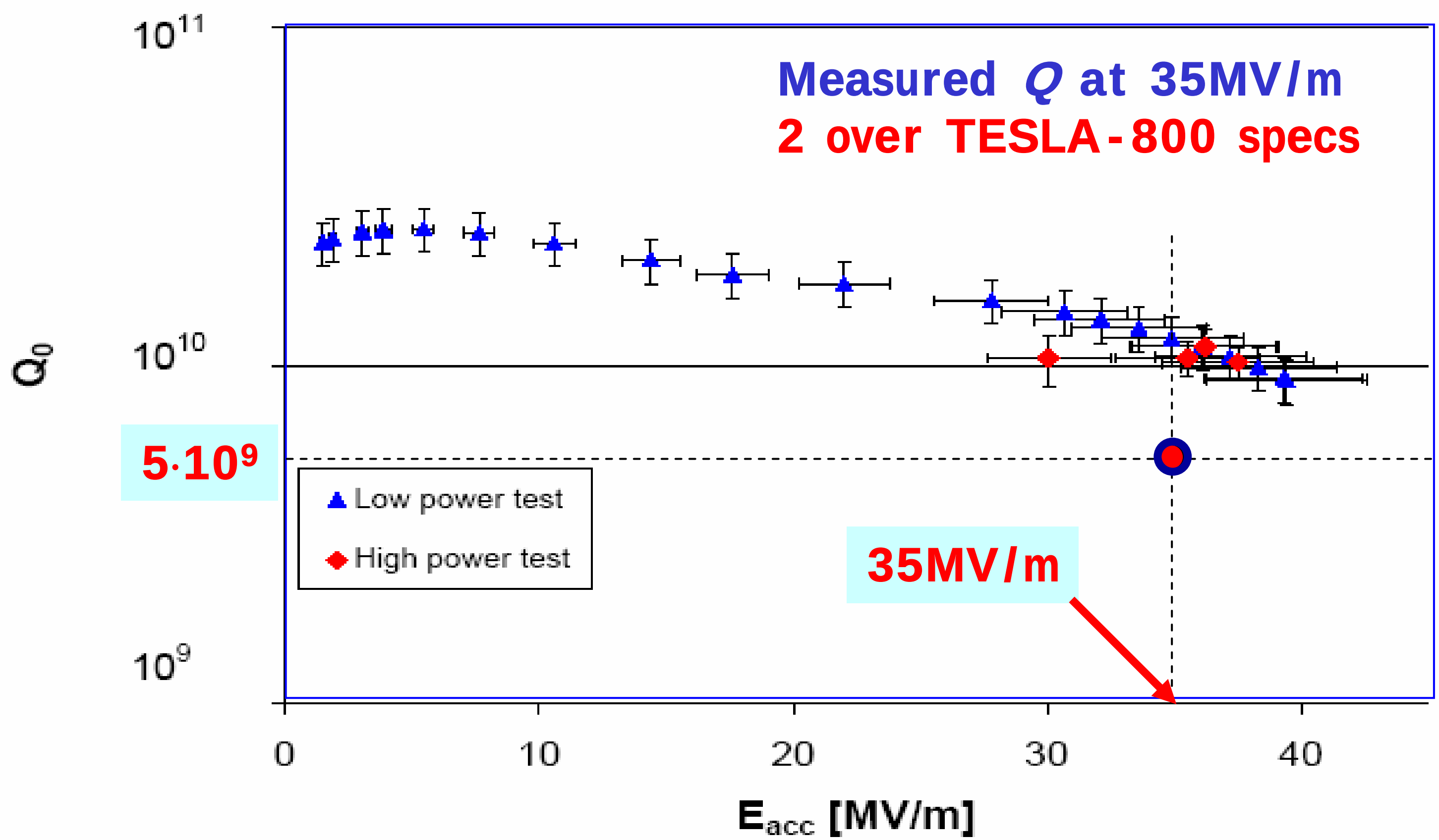
Vertical and System Test in 1/8th Cryomodule (CHECHIA)

800°C annealing

Low residual resistance

120°C Backing

Low Field Emission/Dark Current

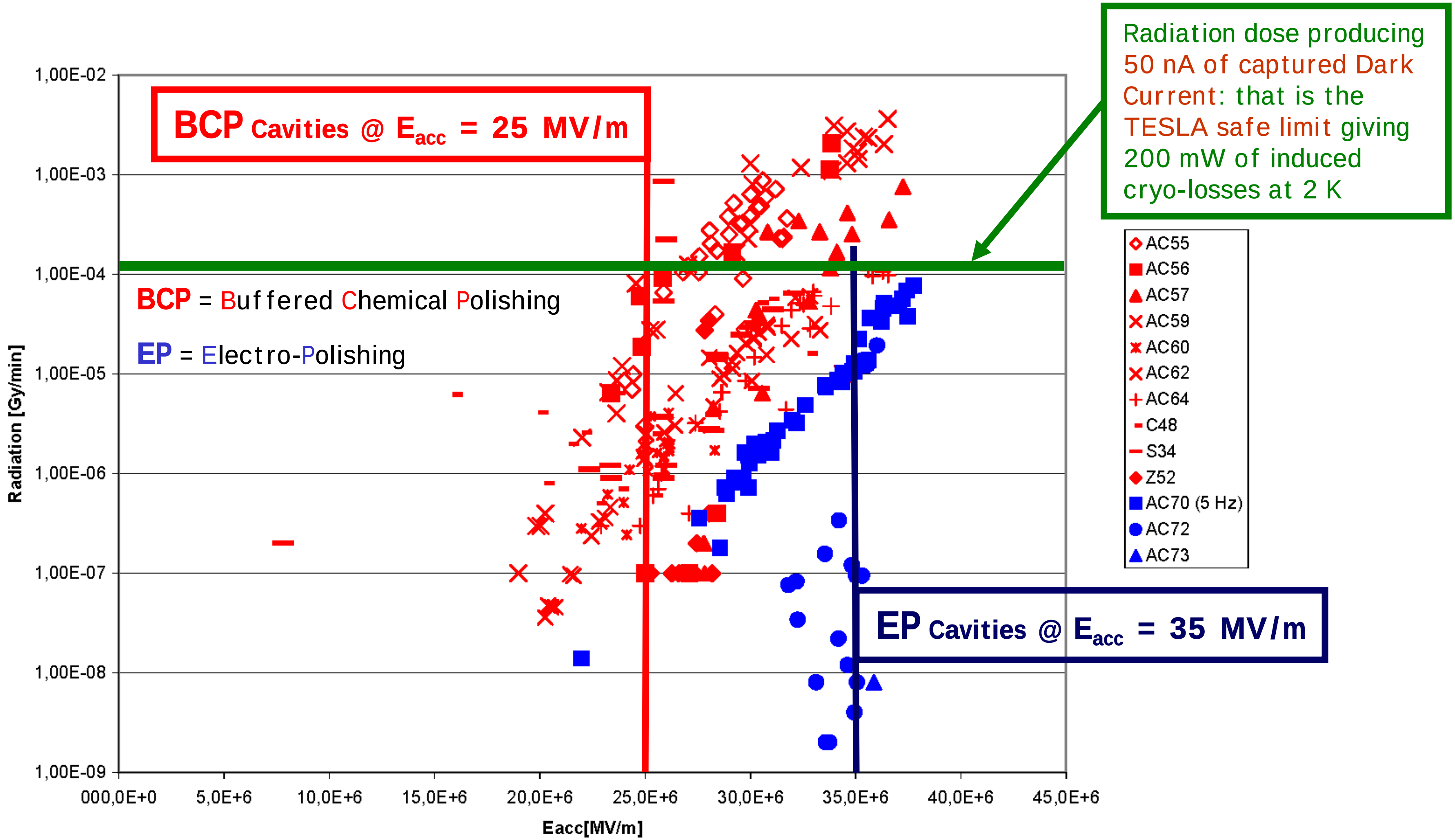


Field Emission pushed to very high field

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

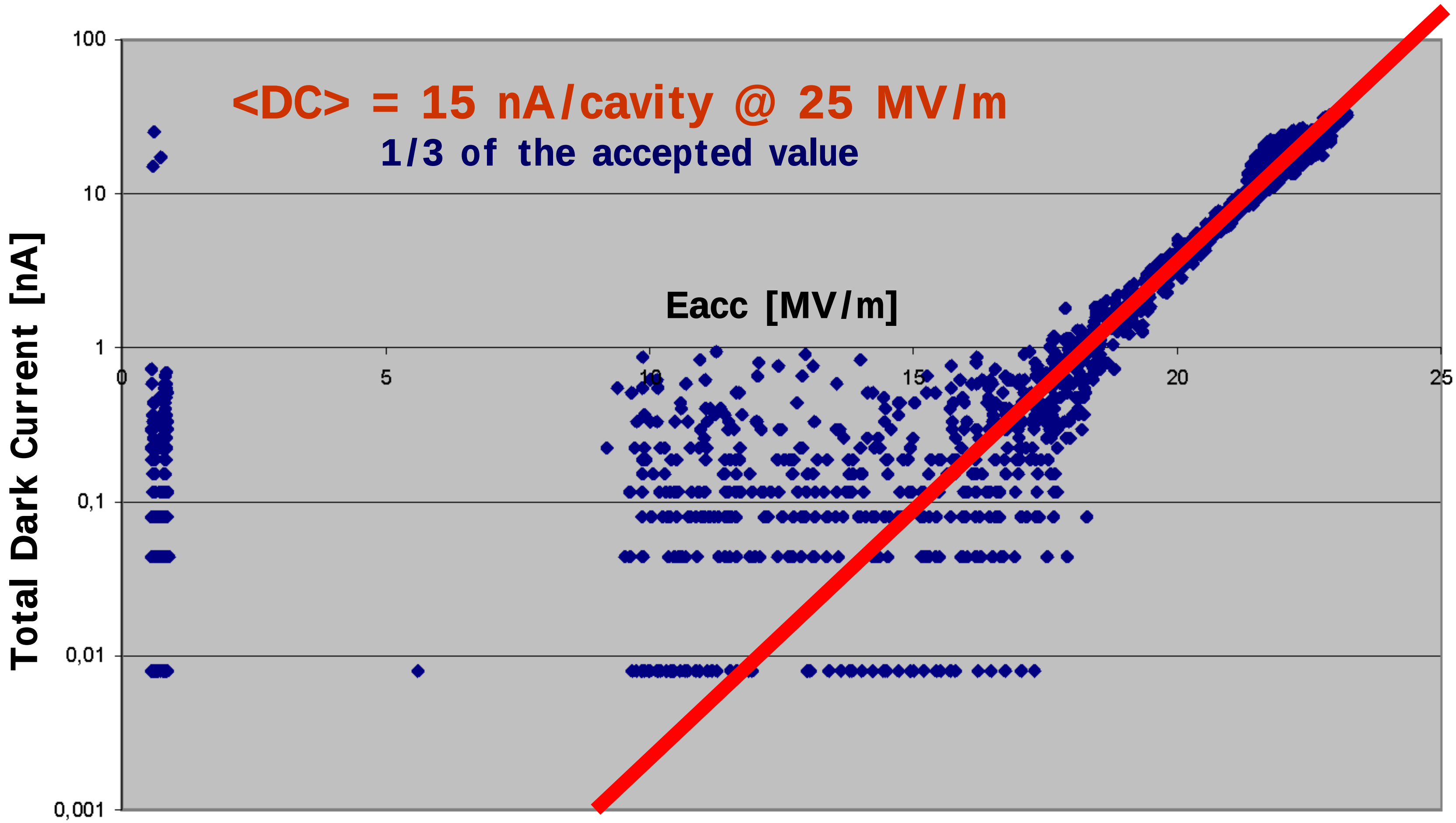


Dark Current Measured on ACC4

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



The 35MV/m Cryomodule Test

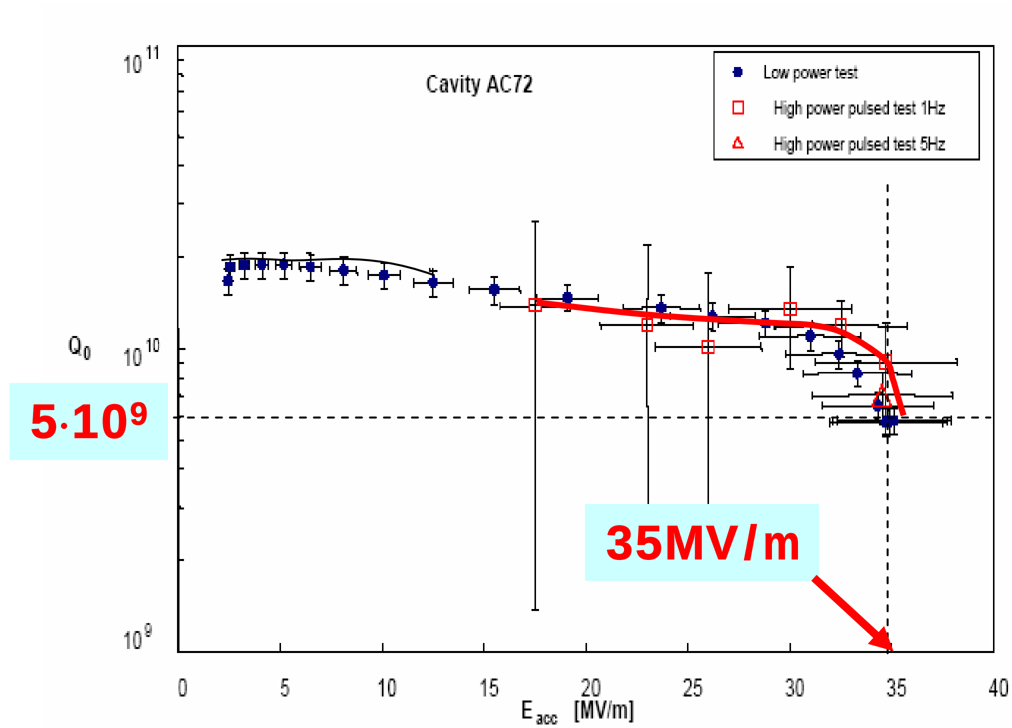
AC72: one of **five** high-performance EP cavities

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

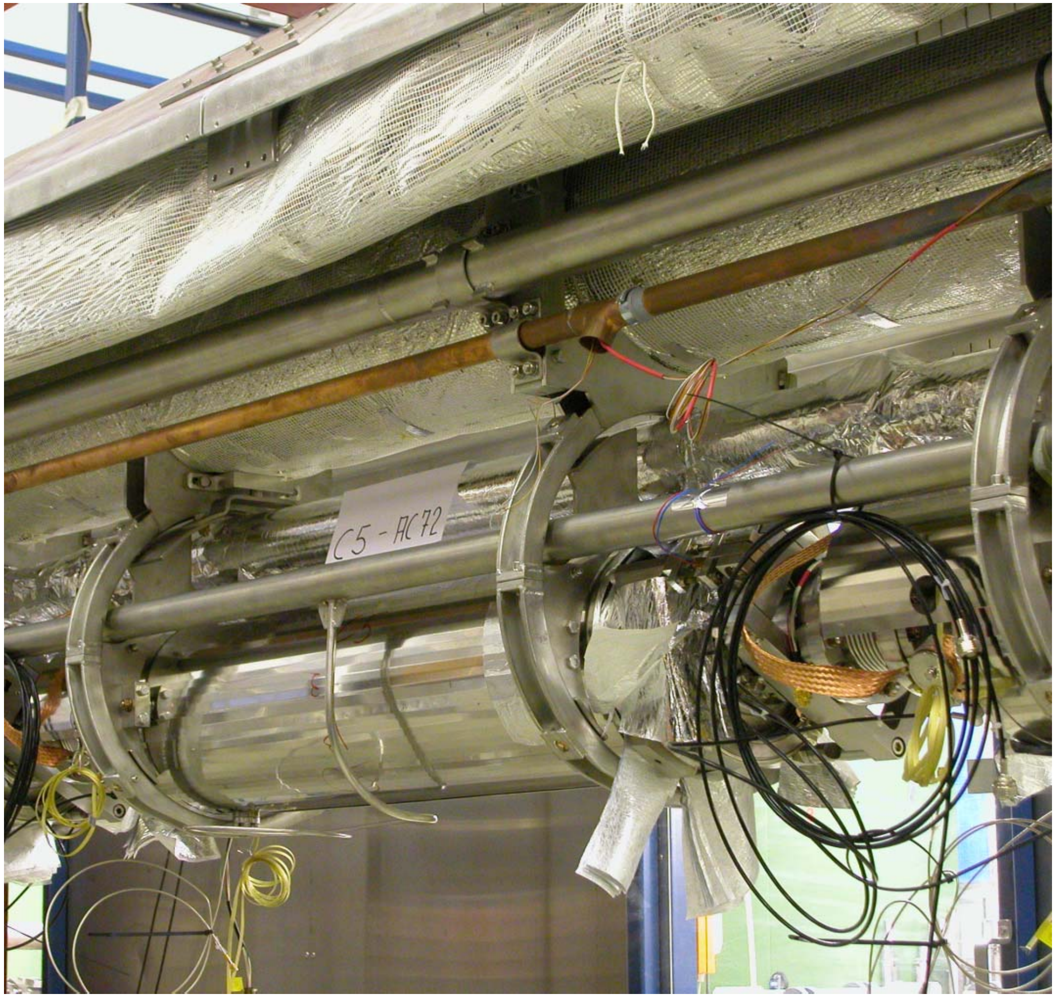
Acceptance test in vertical cryostat

↓ Transferred to

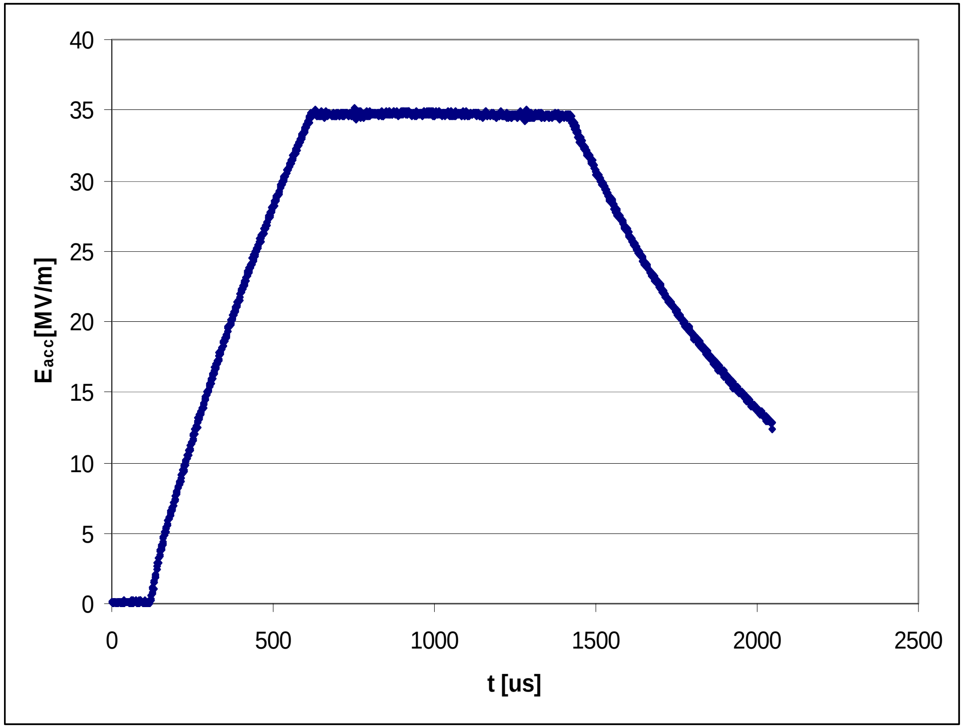
Full 1/8th CM horizontal test (CHECHIA)

↓ Transferred to

Full 8 cavity Cryomodule



The 35MV/m Cryomodule Test



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

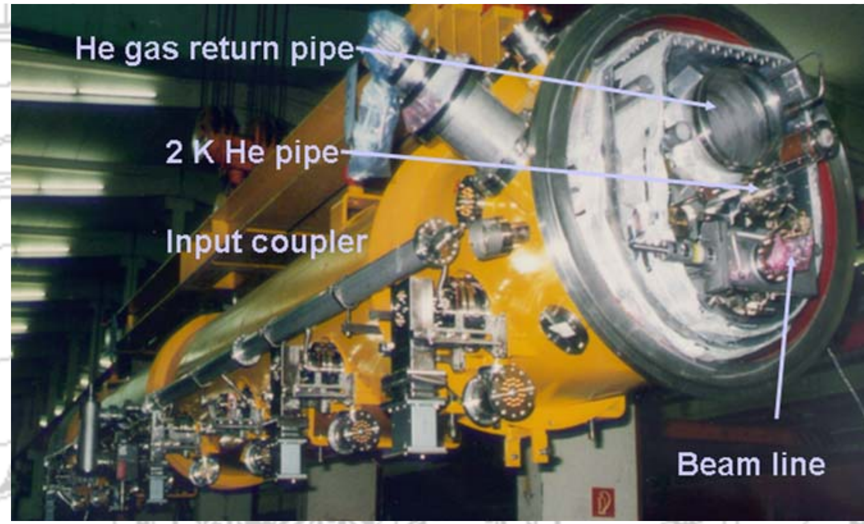
- RF measurements showed no degradation of performance (35MV/m achieved)
- RF gradient measurement calibrated using beam (energy spectrometer)
- No measurable radiation detected (no dark current)

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

Performing Cryomodules

Three generations of the cryomodule design, with improving simplicity and performances, while decreasing costs

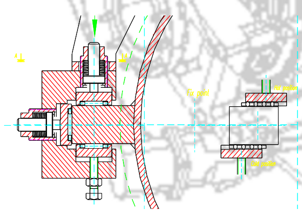


Cryomodule Characteristics

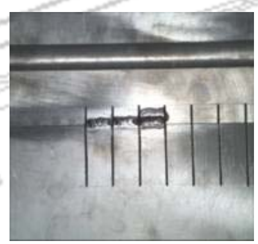
Length		12	m
# cavities		8	
# doublets		1	
Static Losses	@ 2 K	1.5	W
	@ 5 K	8	W
	@ 50 K	70	W

Required plug power **< 6 kW**

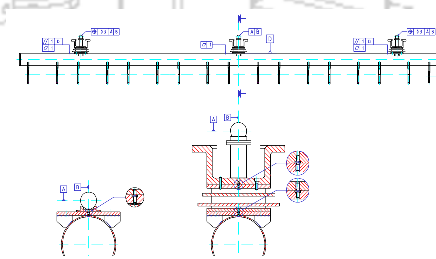
Sliding Fixtures @ 2 K



"Finger Welded" Shields



Reliable Alignment Strategy



String Assembly

The assembly of a string of 8 cavities

- is a standard procedure
- is done by technicians from the TESLA Collaboration
- is well documented using the cavity database as well as an Engineering Data Management System
- was the basis for two industrial studies.

Technology transfer of the complete established procedure to industry ready for the EU X-FEL.

The inter-cavity connection is done in class 10 cleanrooms

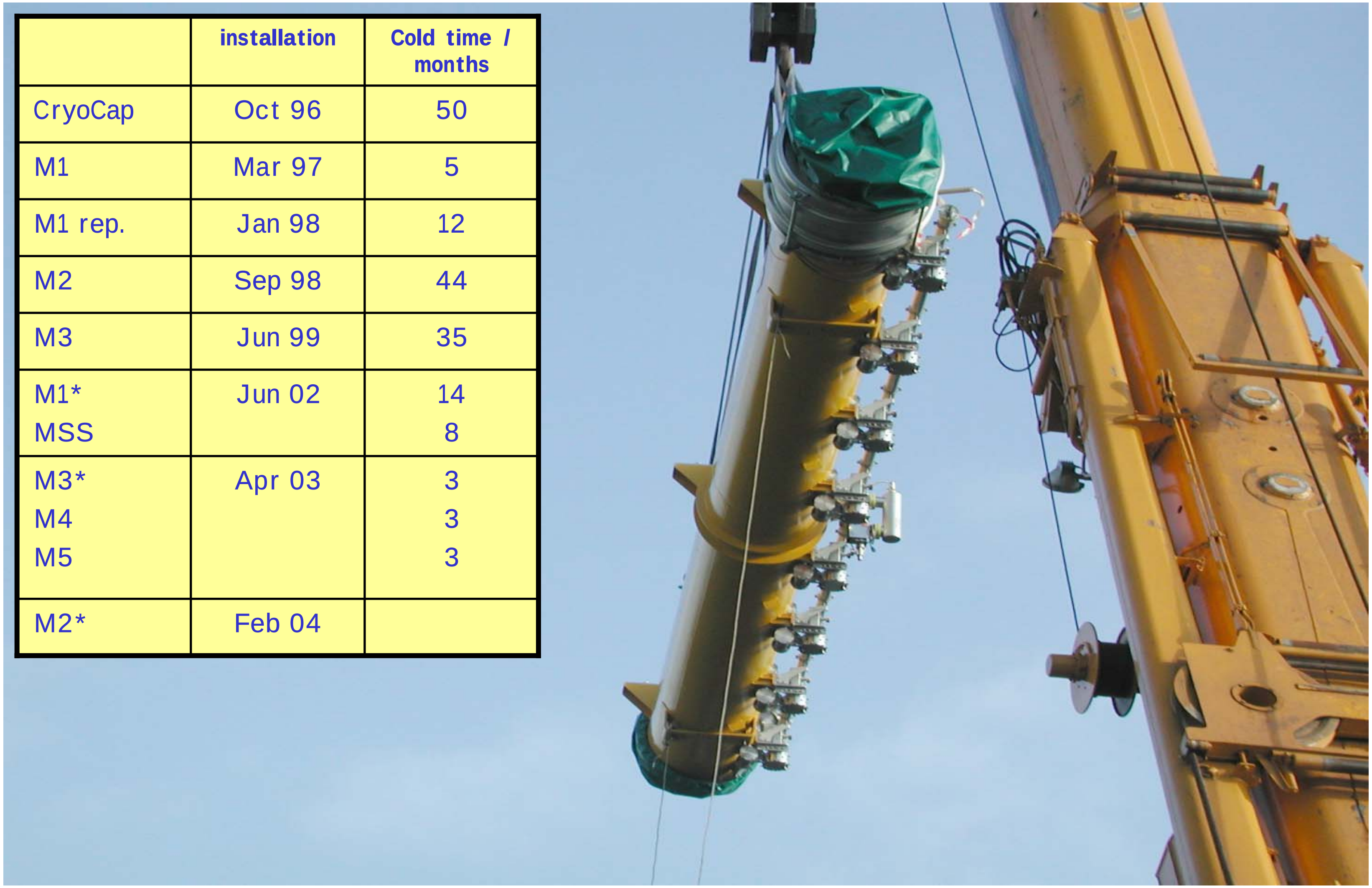
Module Assembly

The module assembly is a well defined and standard procedure.

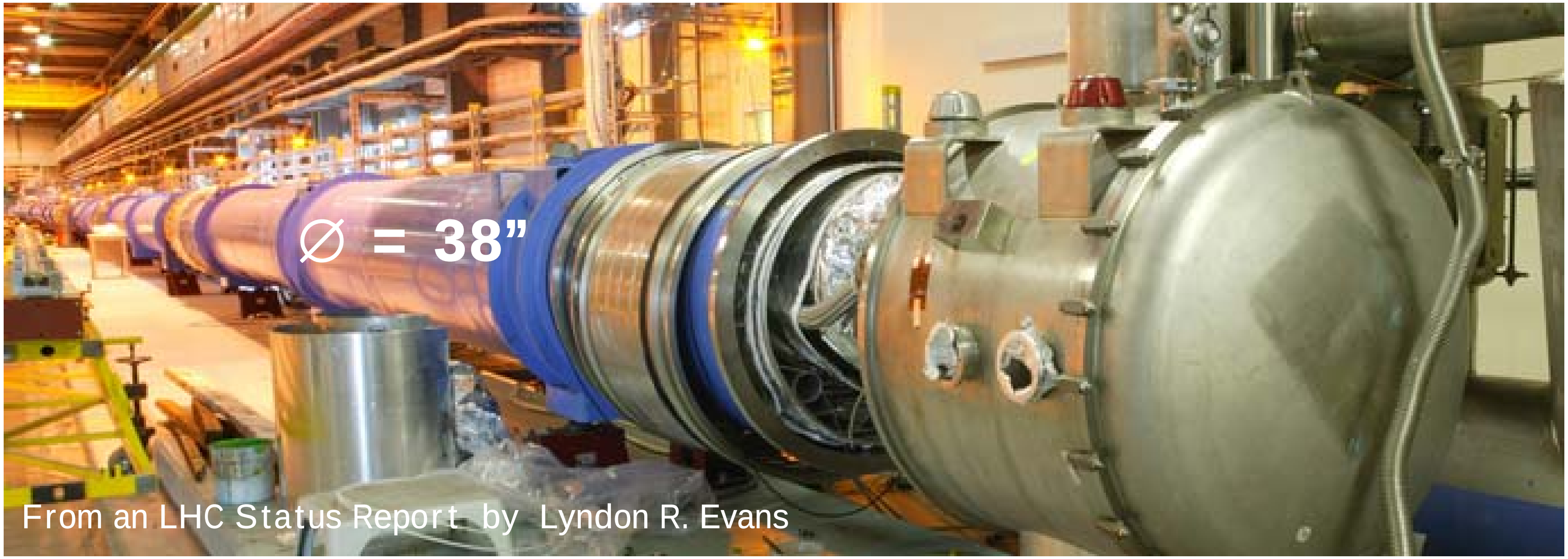
- experience of 10 modules exists
- the latest generation (type III) will be used for series production (XFEL requires 120 modules)
- several cryogenic cycles as well as long time operation were studied
- the assembly problems occurred are well understood and cured

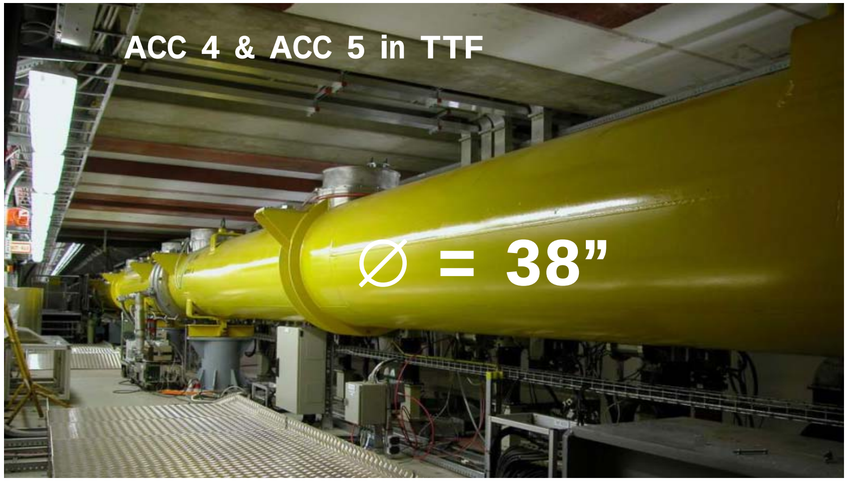
TTF Module Installation

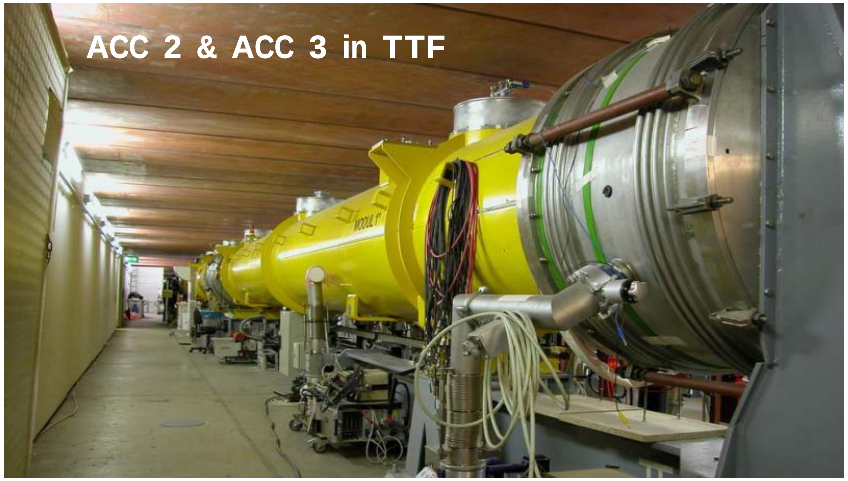
	installation	Cold time / months
CryoCap	Oct 96	50
M1	Mar 97	5
M1 rep.	Jan 98	12
M2	Sep 98	44
M3	Jun 99	35
M1* MSS	Jun 02	14 8
M3* M4 M5	Apr 03	3 3 3
M2*	Feb 04	



LCH and TESLA Module Comparison







Future of SRF Technology

- 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 if the Technology choice will be for cold.
- **The future of TESLA Technology is sure** and somehow LC independent, but it would be **faster** and **cheaper** if a **cold Linear Collider is built**