International Conference on Linear Colliders

Colloque international sur les collisionneurs linéaires

LCWS 04 : 19-23 April 2004 - "Le Carré des Sciences", Paris, France

Present Status of R&D for the Superconducting Linac

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Talk Outline

- Introduction
- The TESLA Challenge
- Status of SRF Cavities
- Status of Others SC Linac Components
- Ongoing R&D and Perspectives
- Concluding Remarks

Next e+e- collider must be linear

- Synchrotron Radiation (SR) becomes prohibitive for electrons in a circular machine above LEP energies:

$$U_{SR}[\text{GeV}] = 6 \cdot 10^{-21} \cdot \gamma^4 \cdot 1 / r[\text{km}]$$

U_{SR}	=	energy loss per turn
γ	=	relativistic factor
r	=	machine radius

- RF system must replace this loss, and r scale as E^2
- LEP @ 100 GeV/beam: 27 km around, 2 GeV/turn lost
- Possible scale to 250 GeV/beam i.e. **E_{cm} = 500 GeV**:
  - **170 km** around
  - **13 GeV/turn** lost

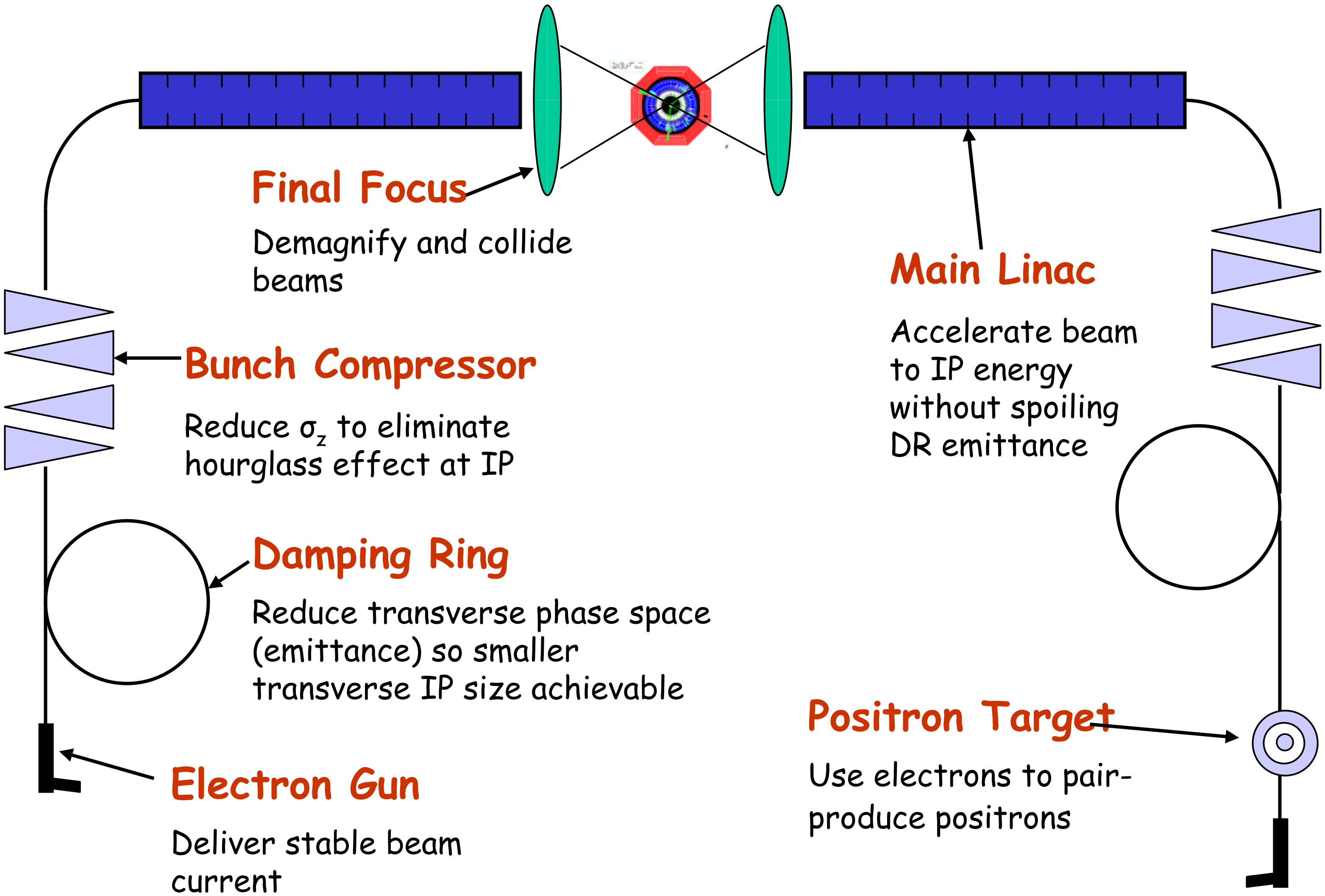
$\gamma_{250GeV} = 4.9 \cdot 10^5$

- Consider also the luminosity
  - For a **luminosity of ~ 10^{34}/cm^2/second**, scaling from b-factories gives ~ 1 Ampere of beam current
  - 13 GeV/turn x 2 amperes = **26 GW RF power**
  - Because of conversion efficiency, this collider would consume more power than the state of **California in summer: ~ 45 GW**

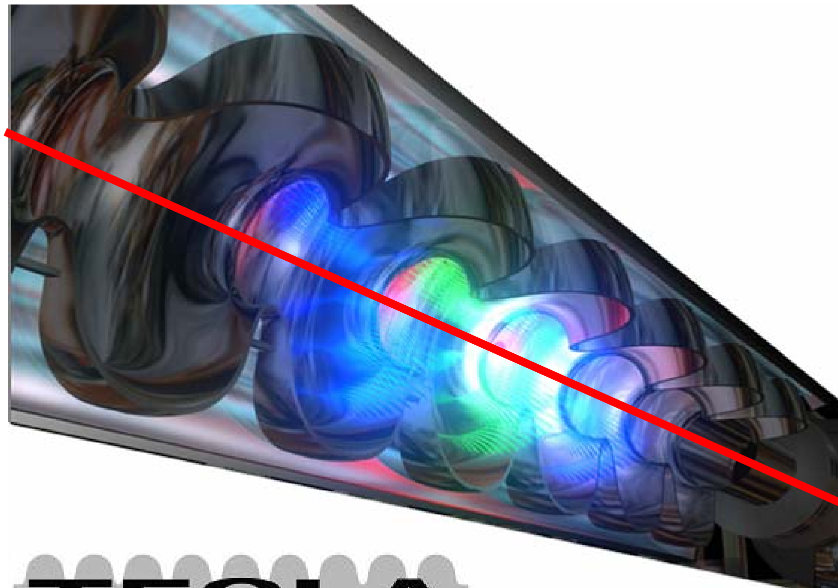
Circulating beam power = 500 GW

- Both size and power seem excessive

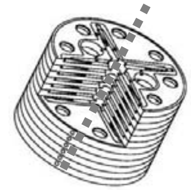
LC conceptual scheme



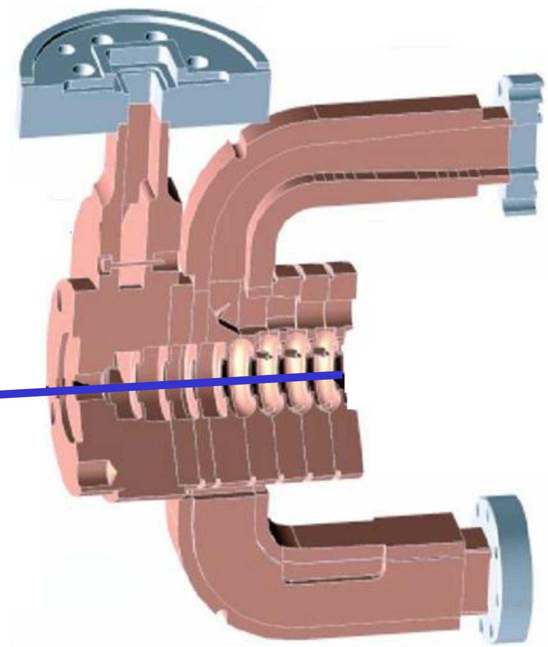
Competing technologies



1.3 GHz - Cold



30 GHz-Warm

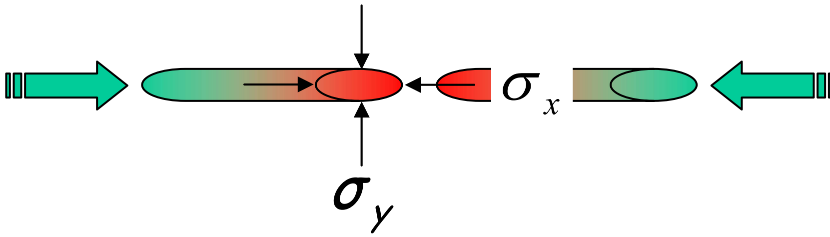


NLC

11.4 GHz - Warm

What to do for Luminosity?

$$L \propto \frac{N_e^2}{\sigma_x \sigma_y}$$



$$L \propto n_b \times f_{rep}$$

L = Luminosity
N_e = # of electron per bunch
$\sigma_{x,y}$ = beam sizes at IP
IP = interaction point

$$L \propto \frac{P_b}{E_{c.m.}} \times \frac{N_e}{\sigma_x \sigma_y}$$

n_b = # of bunches per pulse
f_{rep} = pulse repetition rate
P_b = beam power
$E_{c.m.}$ = center of mass energy

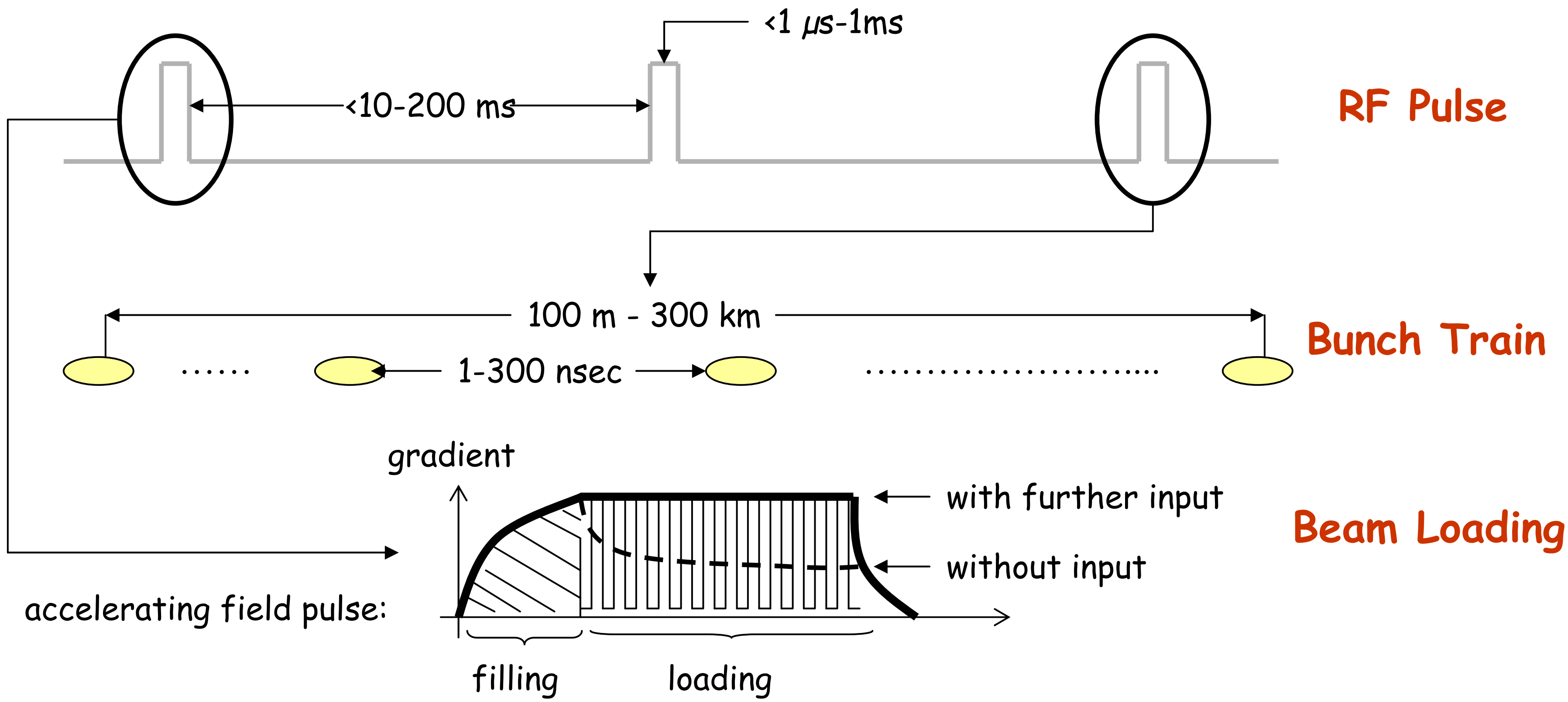
Parameters to play with

- ↓ Reduce **beam emittance** $(\varepsilon_x \cdot \varepsilon_y)$ for smaller beam size $(\sigma_x \cdot \sigma_y)$
- ↑ Increase bunch population (N_e)
- ↑ Increase beam power $(P_b \propto N_e \times n_b \times f_{rep})$
- ↑ Increase **beam to-plug power efficiency** for cost

Linear Colliders are pulsed

LCs are pulsed machines to improve efficiency. As a result:

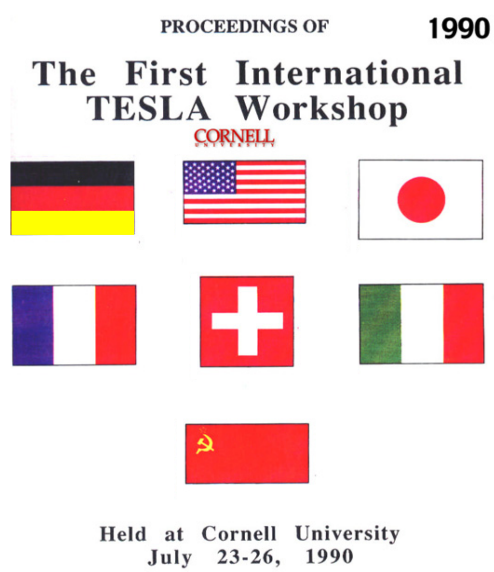
- duty factors are small
- pulse peak powers can be very large

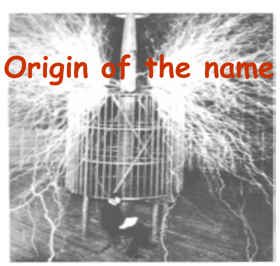


The TESLA challenge

Use **Superconducting RF**: Higher Conversion Efficiency
Smaller Emittance Dilution

Physical limit at 50 MV/m → ≥25 MV/m should be possible
→ Common R&D effort for TESLA

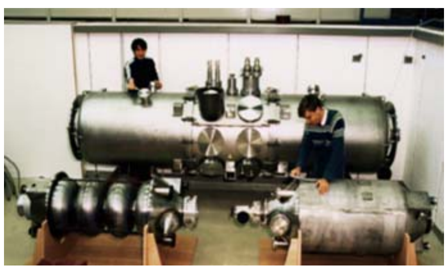


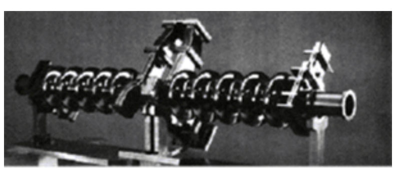


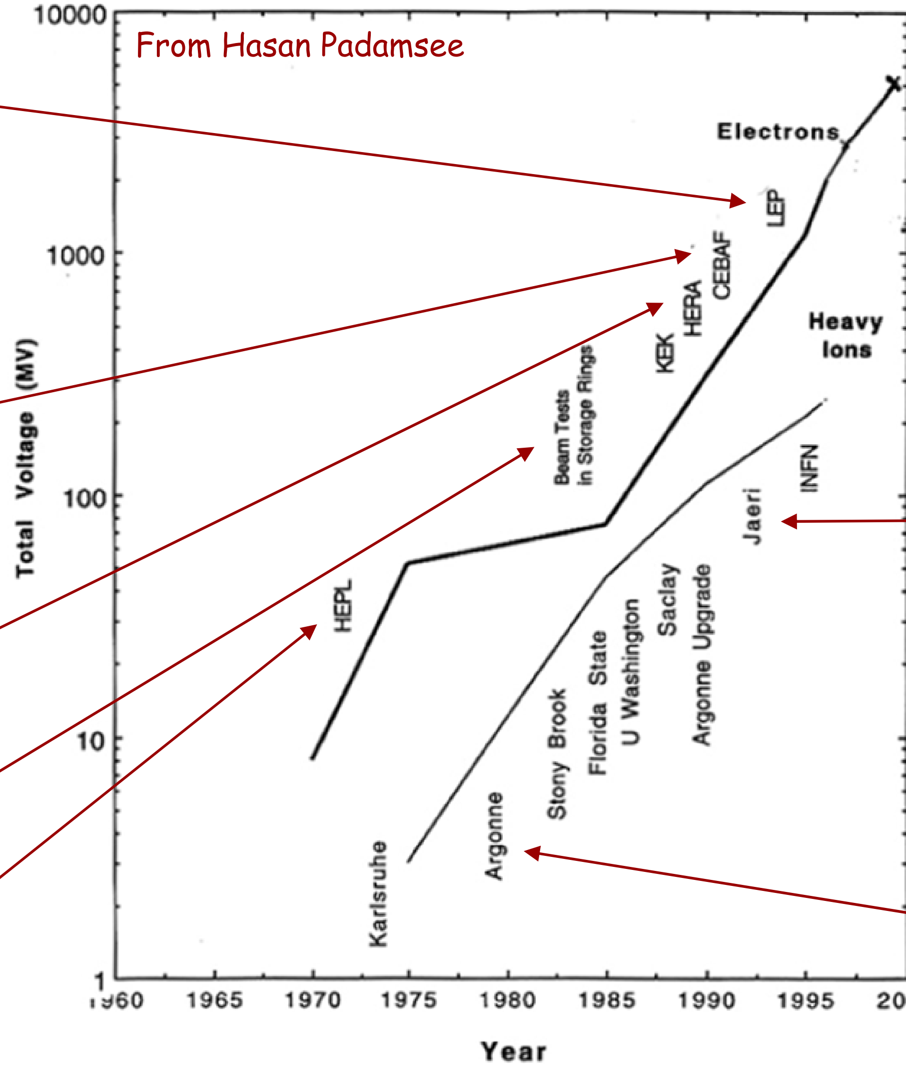
1992 - TESLA Collaboration set up at DESY

TESLA

SRF before TESLA





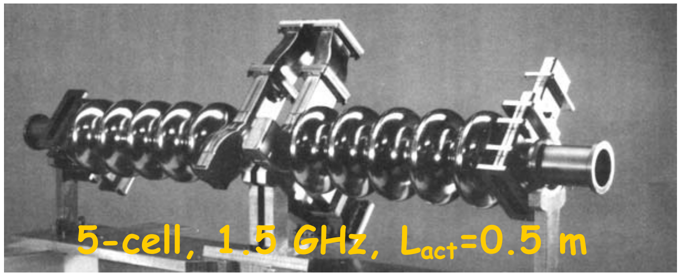


Total >1000 meters
> 5 GV

Examples: CEBAF, LEPII, HERA

1984/85: First great success

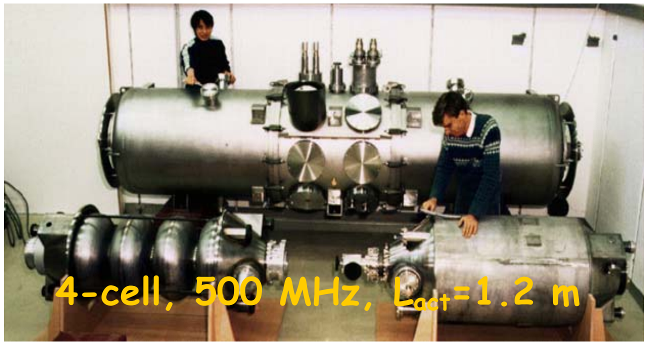
- A pair of 1.5 GHz cavities developed and tested (in CESR) at Cornell
- **> 300 cavities produced for CEBAF** at TJNAF for a nominal E_{acc} = 5 MV/m



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
- **Field improved with time** $\langle E_{acc} \rangle$ = 7.8 MV/m (Cryo-limited)

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



Limiting Problems before TESLA

Poor material properties

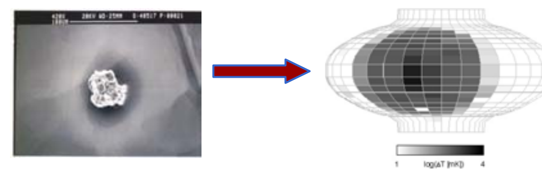
- Moderate Nb purity (Niobium from the Tantalum production)
- Low Residual Resistance Ratio, RRR ⟶ Low thermal conductivity
- Normal Conducting inclusions ⟶ Quench at moderate field

Poor cavity treatments and cleanness

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

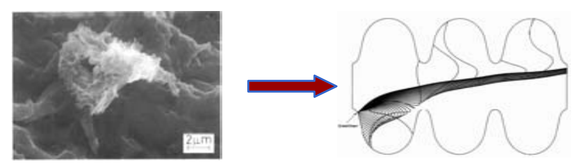
Quenches/Thermal breakdown

- Low RRR and NC inclusions



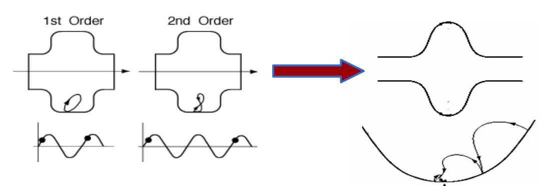
Field Emission

- Poor cleaning procedures and material



Multipactoring

- Simulation codes not sufficiently performing

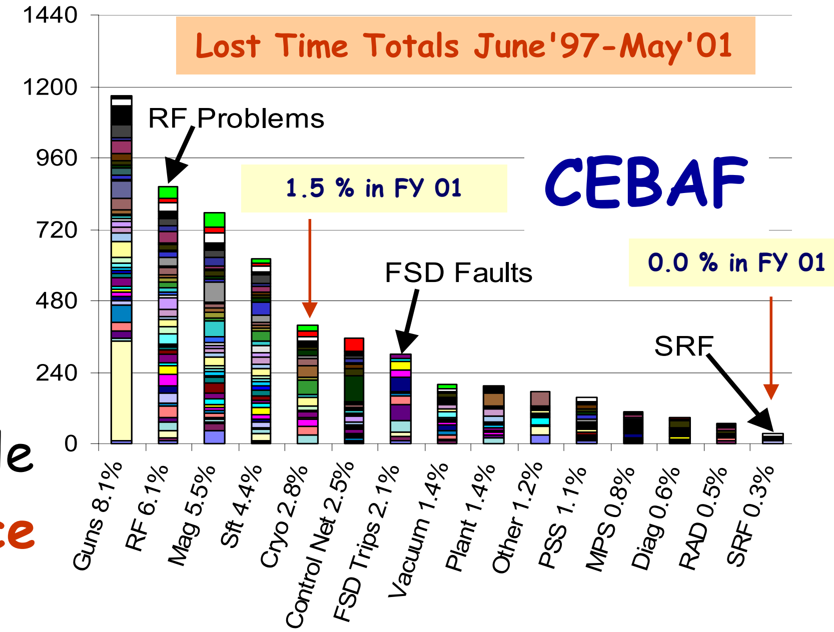


Q-drop at moderate field

Important lessons learned

When not limited by a hard quench (material defect)

Accelerating field improves with time



Large cryo-plants are highly reliable

Negligible lost time for cryo and SRF

Once dark current is set to be negligible

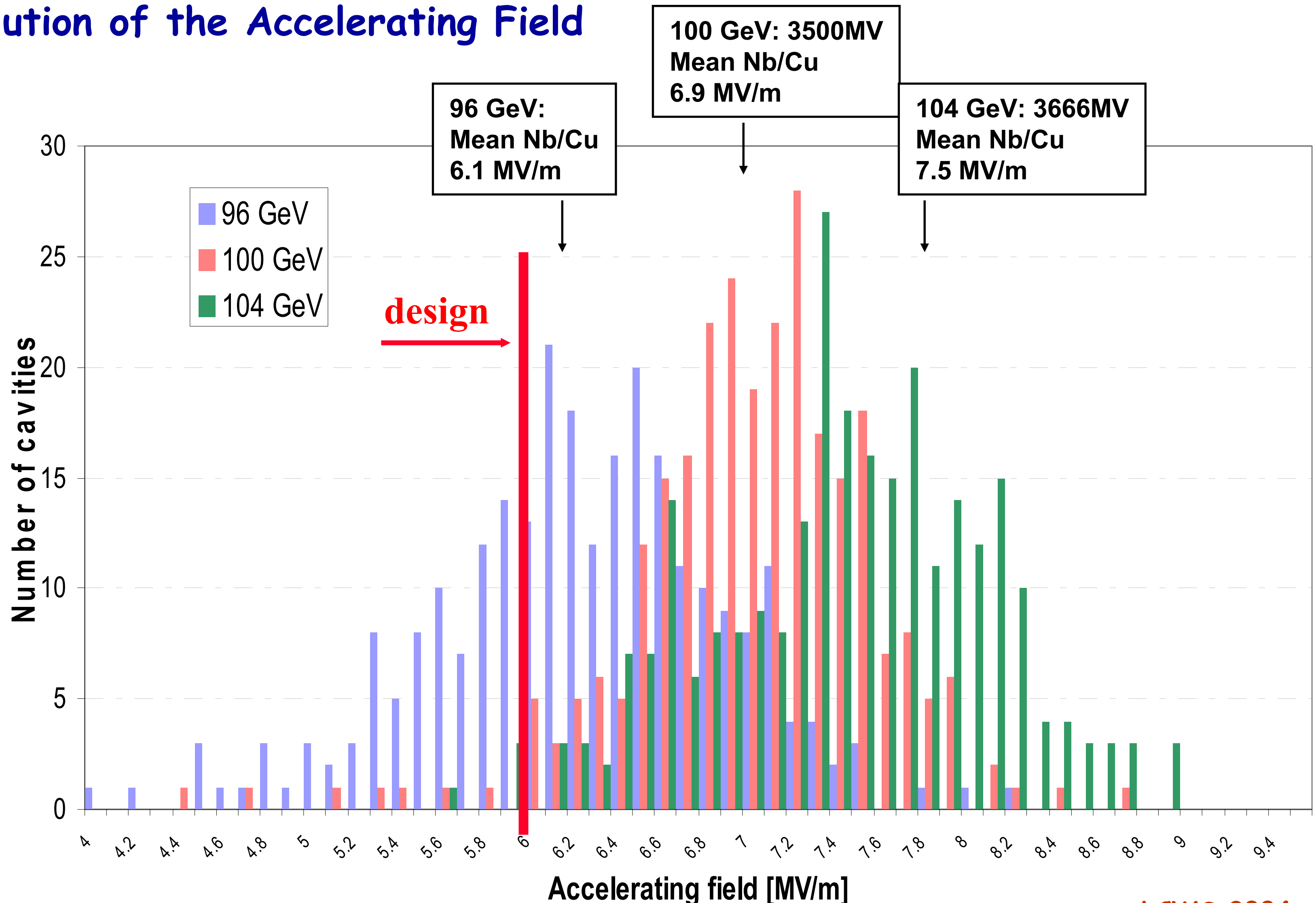
No beam effect on cavity performance

Once procedures are understood and well specified

Industry can produce status of art cavities and cryo-plants

The LEP Cavity Experience

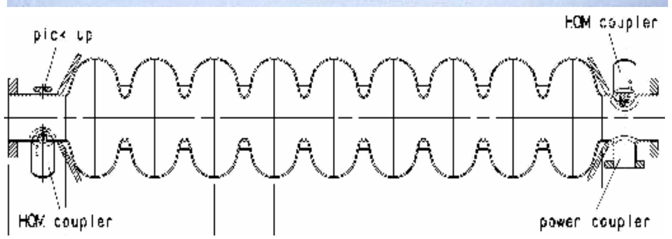
Evolution of the Accelerating Field



The 9-cell TESLA cavity

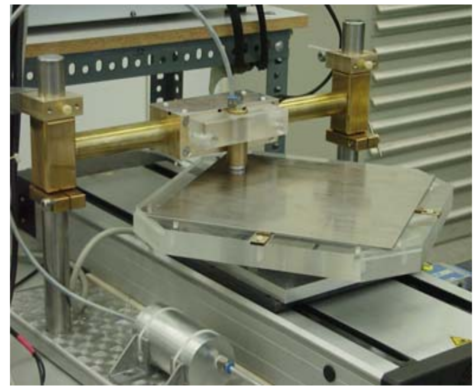
Major contributions from: CERN, Cornell, DESY, CEA-Saclay

- **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
$K_{Lorentz}$	$\approx$ -1	$Hz/(MV/m)^2$



Eddy-current scanning system for niobium sheets

Cleanroom handling of niobium cavities

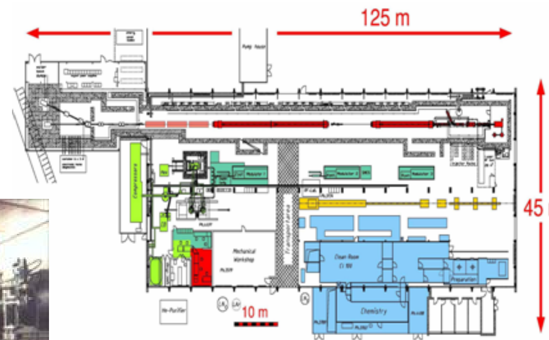
Preparation Sequence

- 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

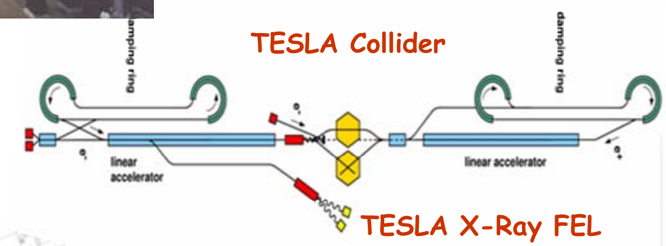
TESLA Collaboration Milestones

- February 1992 – 1° TESLA Collaboration Board Meeting @ DESY
- March 1993 - "A Proposal to Construct and Test Prototype Superconducting RF Structures for Linear Colliders"
- **1995 – 25 MV/m in multi-cell cavity**
- May 1996 – First beam at TTF
- March 2001 – First SASE-FEL Saturation at TTF
- March 2001 – TESLA Technical Design Report
- February 2003 –TESLA X-FEL proposed as an European Facility, 50% funding from Germany
- 2004 – TTF II Commissioning
- **April 2004 - 35 MV/m with beam**

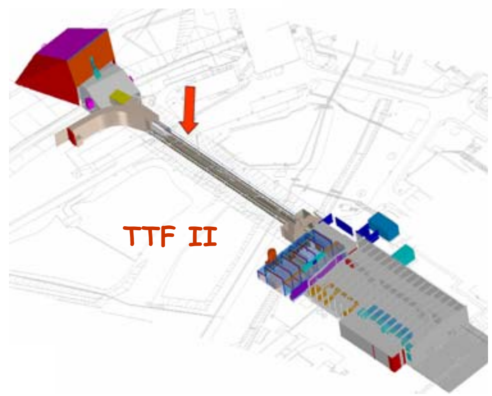
Infrastructure @ DESY in Hall 3



TTF I



TTF II



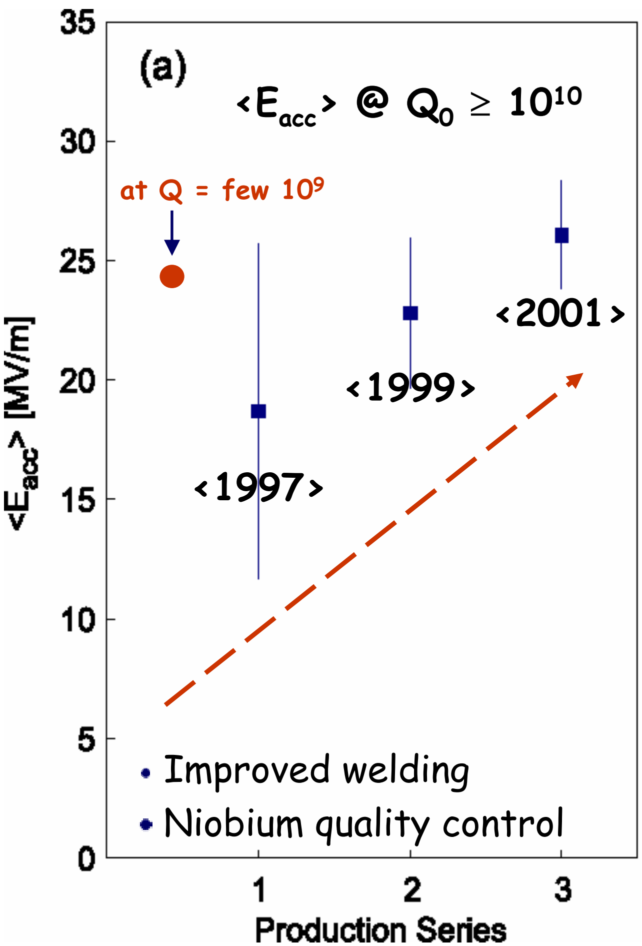
Learning curve with BCP

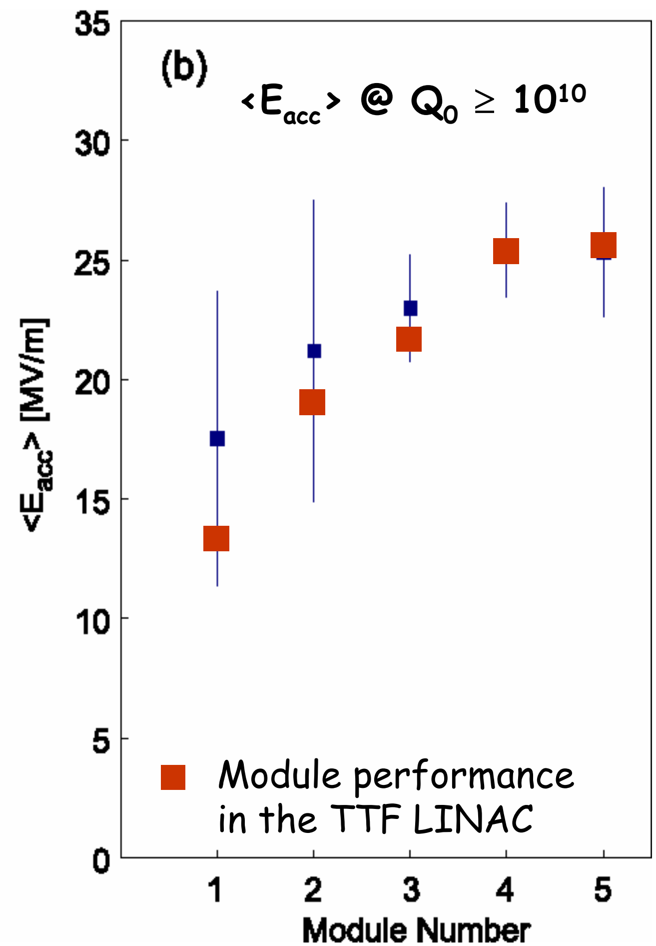
BCP = Buffered Chemical Polishing

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

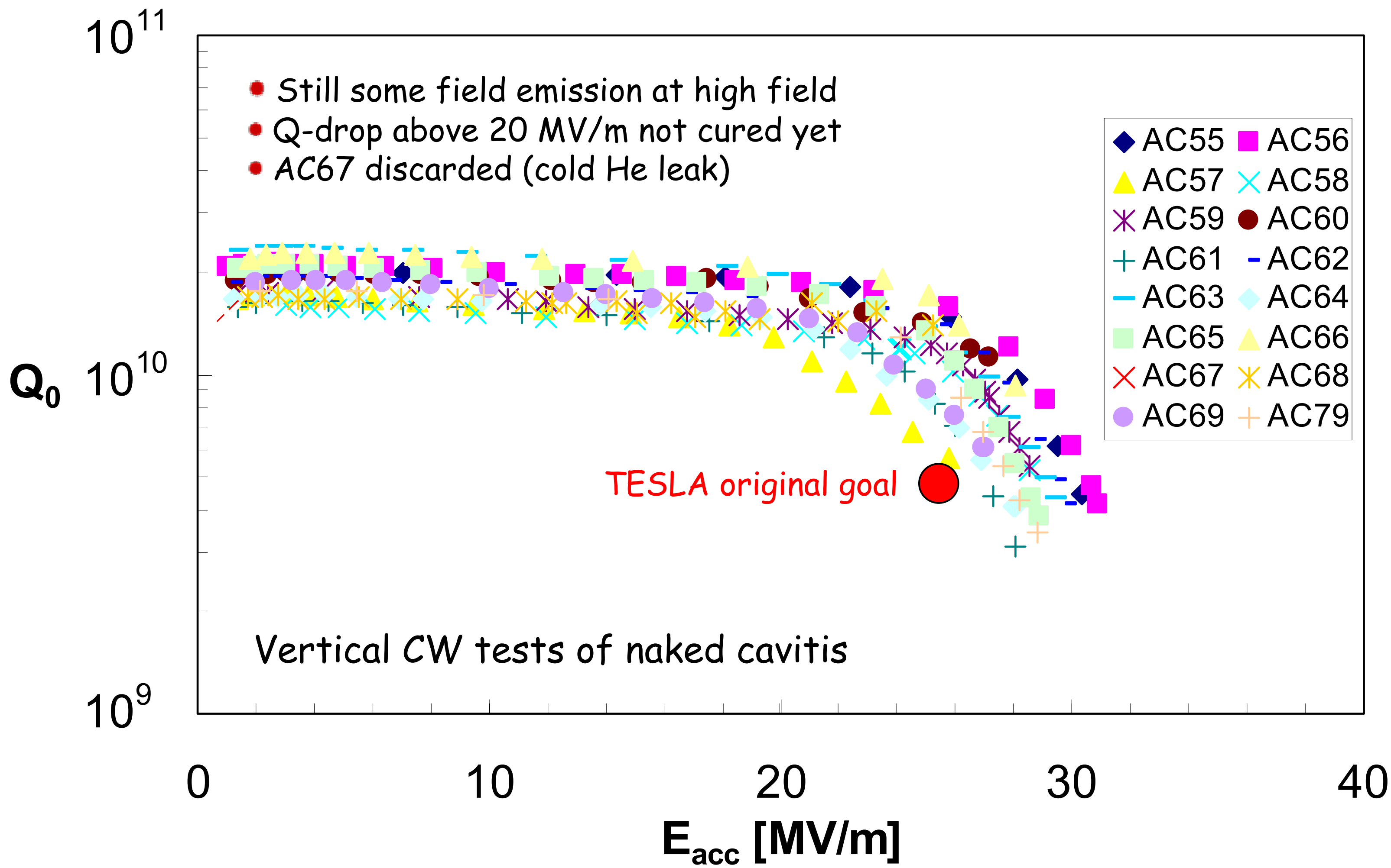
Cornell 1995

5-cell



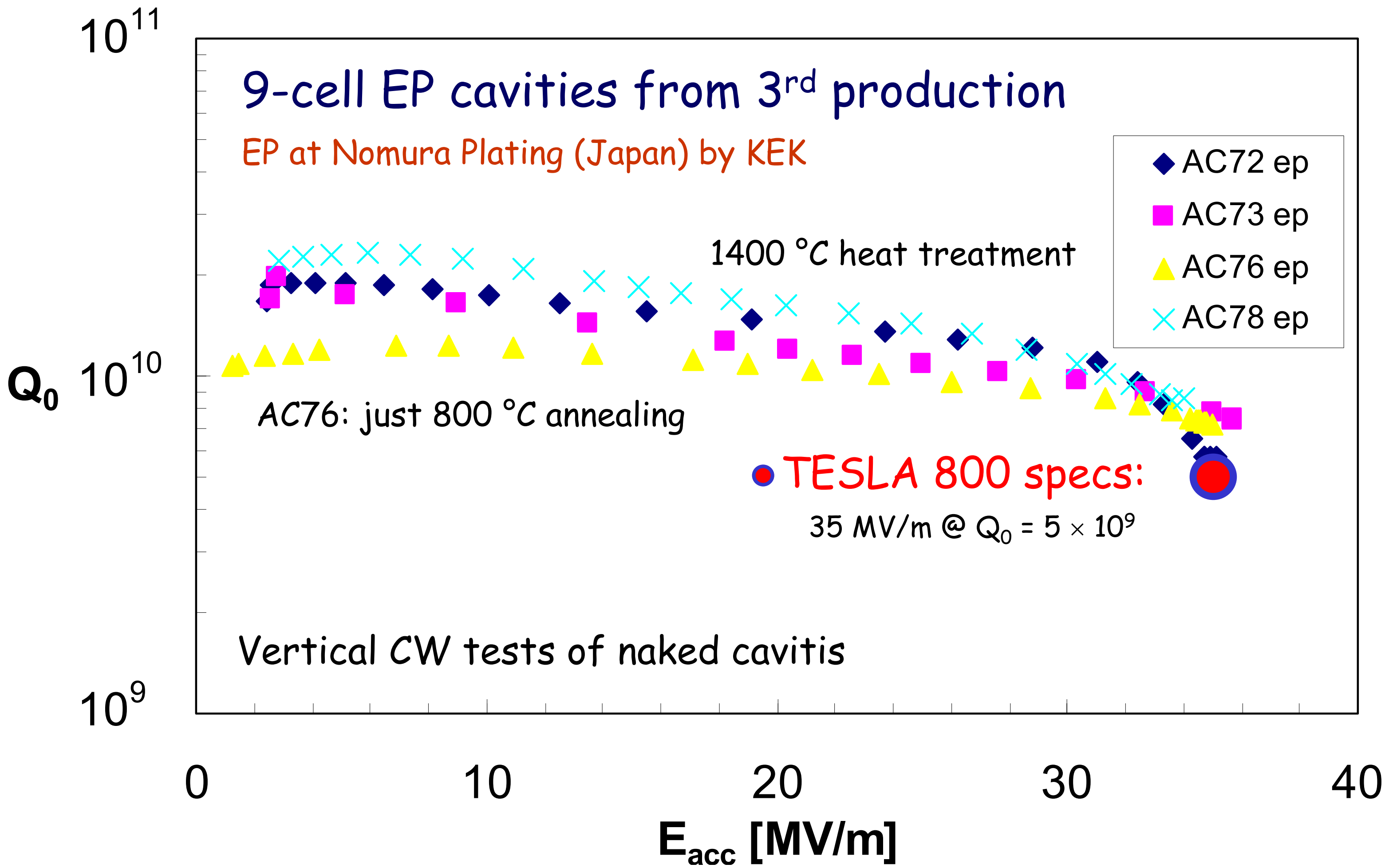


3rd cavity production with BCP



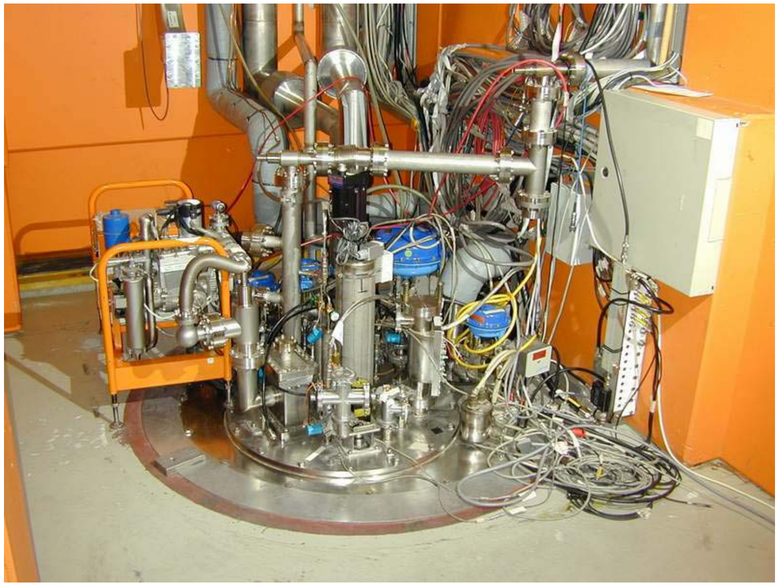
TESLA 800 Performances with EP

EP (Electro-Polishing) developed at KEK by Kenji Saito (originally by Siemens)
Coordinated R&D effort: DESY, KEK, CERN and Saclay



Cavity Vertical Test

- The naked cavity is immersed in a super-fluid He bath.
- High power coupler, He vessel and tuner are not installed
- RF test are performed in CW with a moderate power(< 300W)



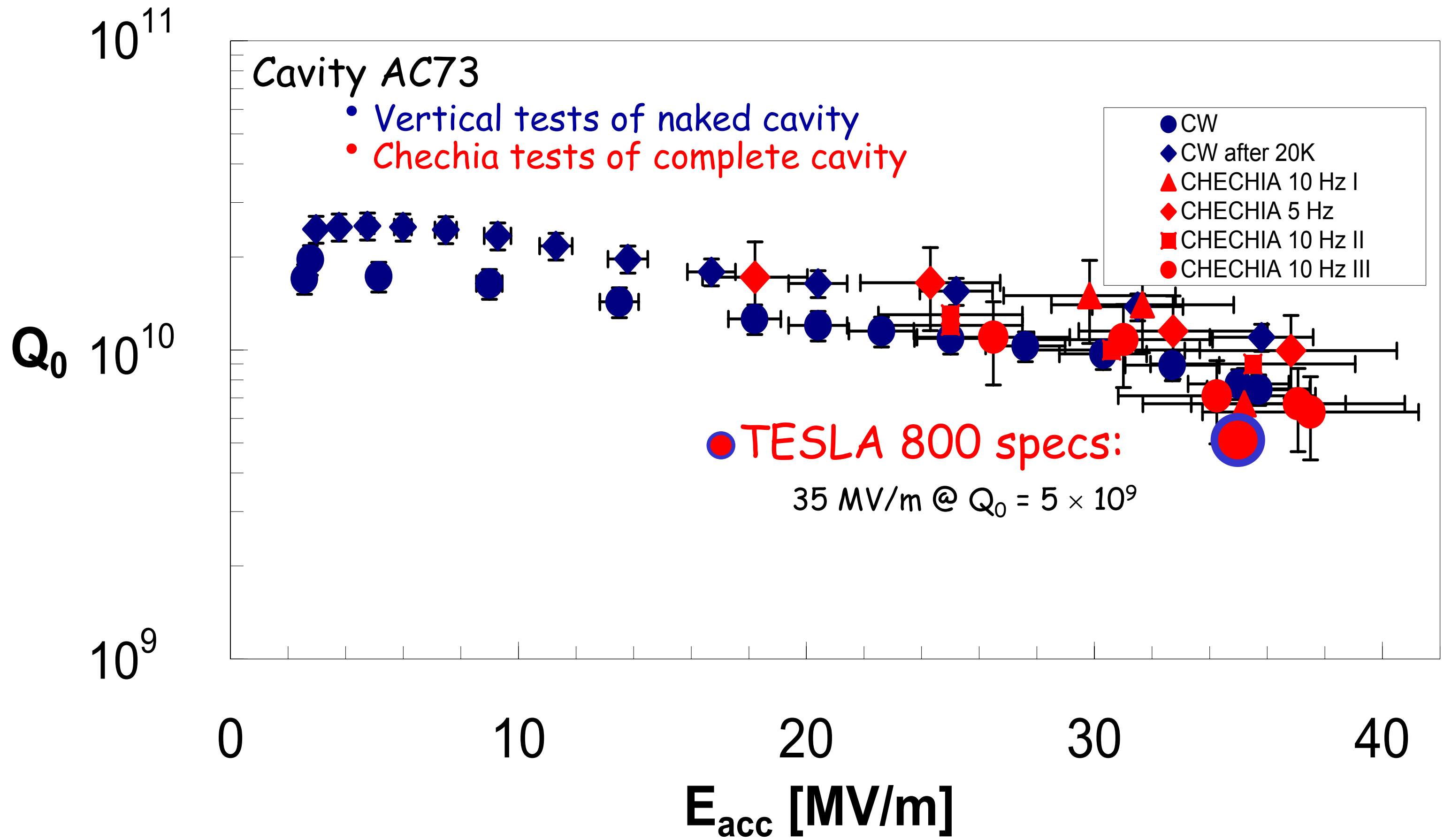
Horizontal tests in "Chechia"

Chechia is a horizontal cryostat to test fully equipped cavities

- 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
- Pulsed RF operation using the same pulse shape foreseen for TESLA

TESLA 800 in "Chechia"

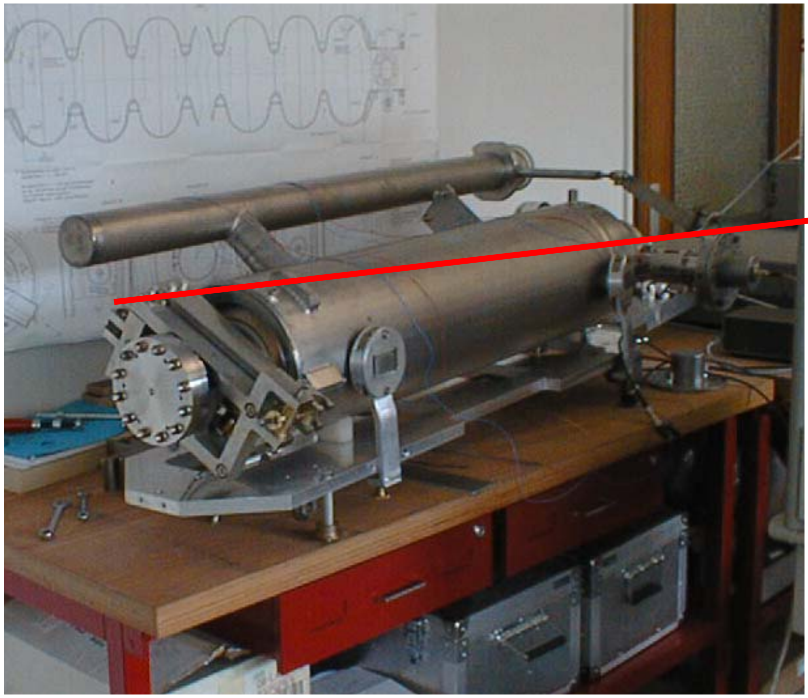
- Long Term (> 1000 h) Horizontal Test
- In Chechia the cavity has all its ancillaries
- Chechia behaves as 1/8th (1/12th) of a TESLA cryomodule

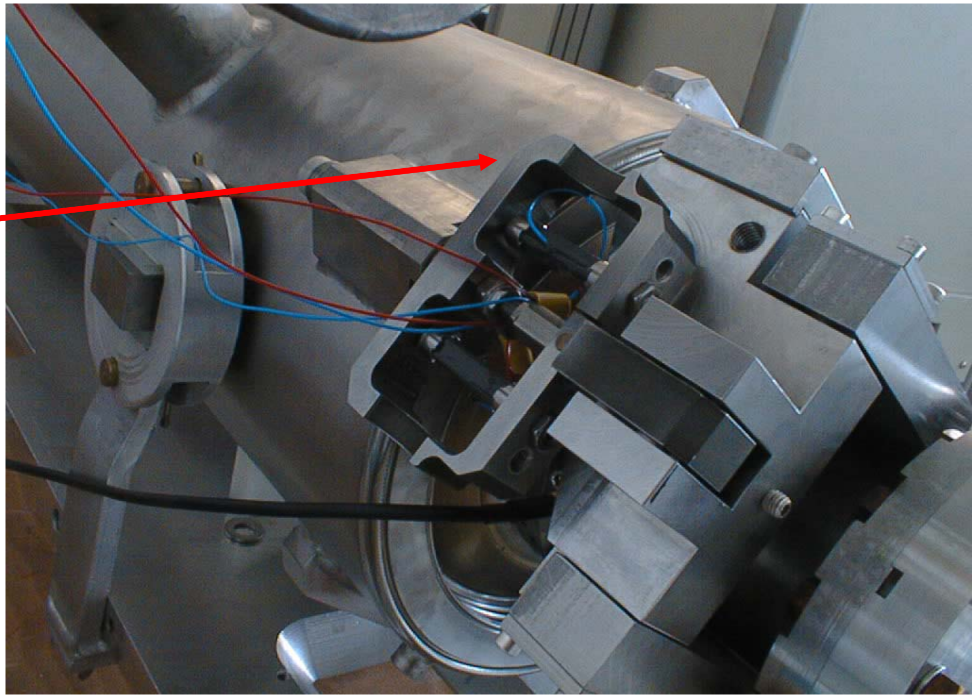


Piezo-assisted Tuner on AC73

- To compensate for Lorentz force detuning during the 1 ms RF pulse
  Feed-Forward

- To counteract mechanical noise, “microphonics”
  Feed-Back

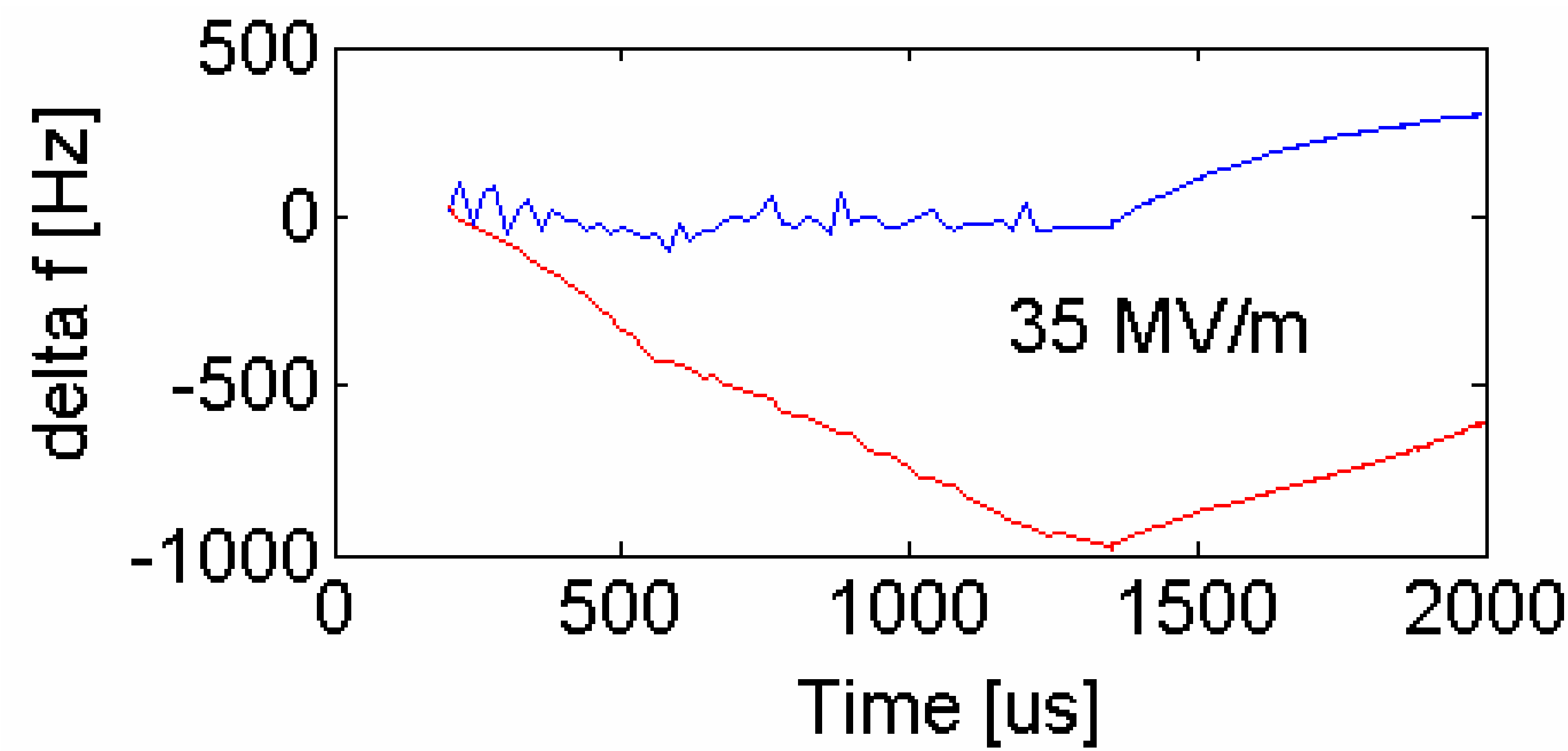




Successful Compensation @ 35 MV/m

Cavity detuning induced by Lorentz force during the tests performed in Chechia at **TESLA-800 specs**

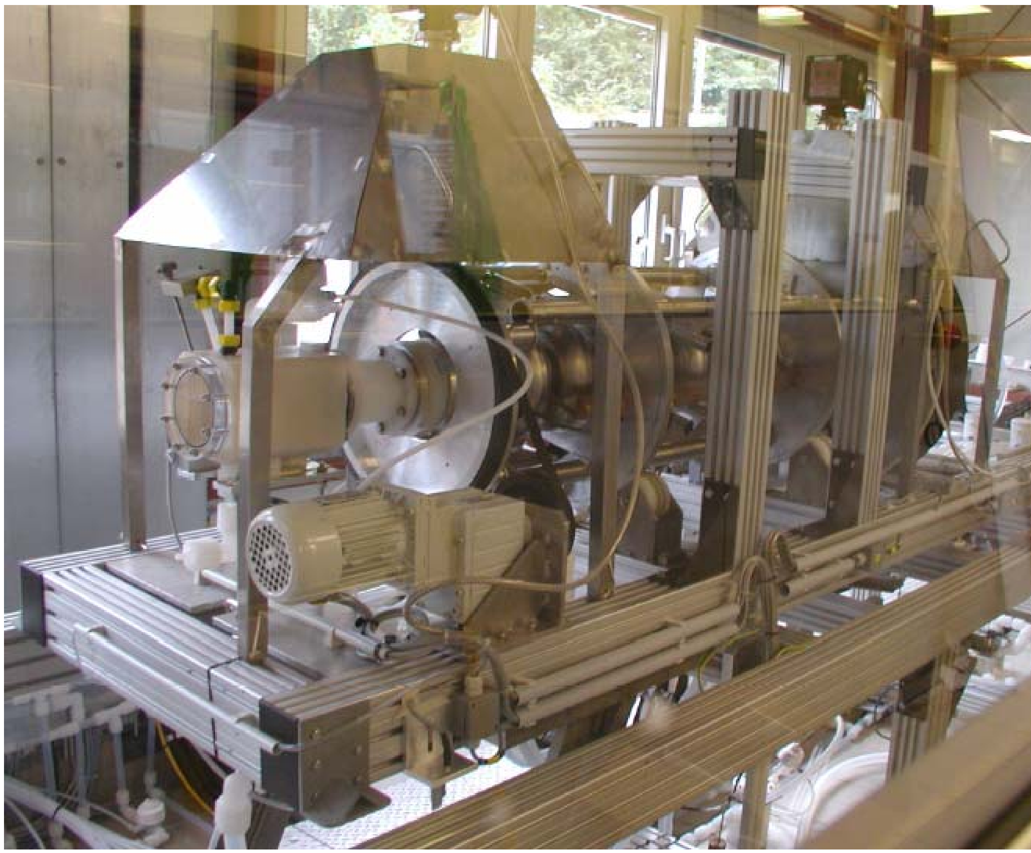
- Piezo-compensation on: just feed-forward resonant compensation
- Piezo-compensation off



EP at DESY fully commissioned

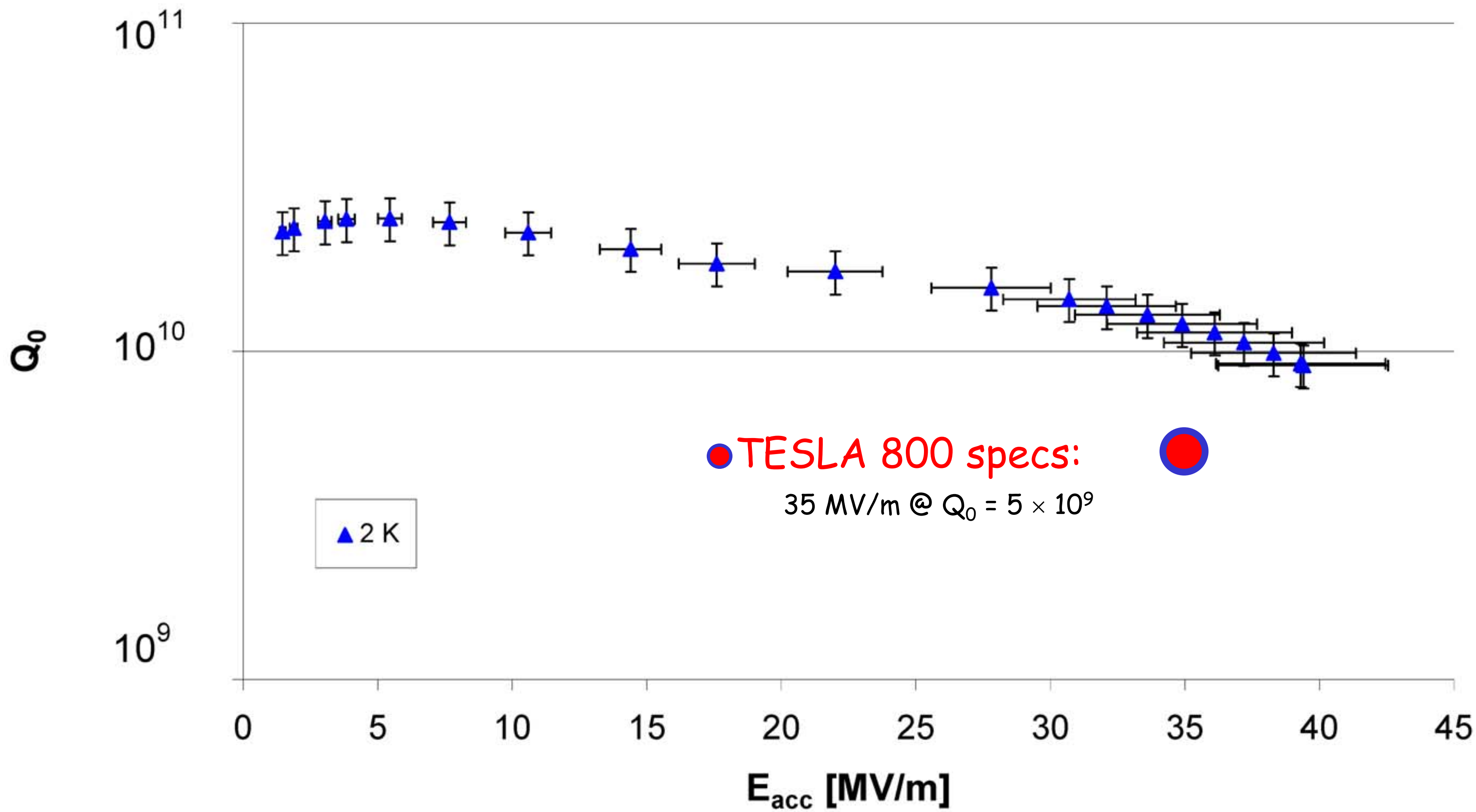
DESY EP Infrastructure fully operational

- outstanding results recently obtained
- 1400°C treatment not required



Results on AC70 - 1

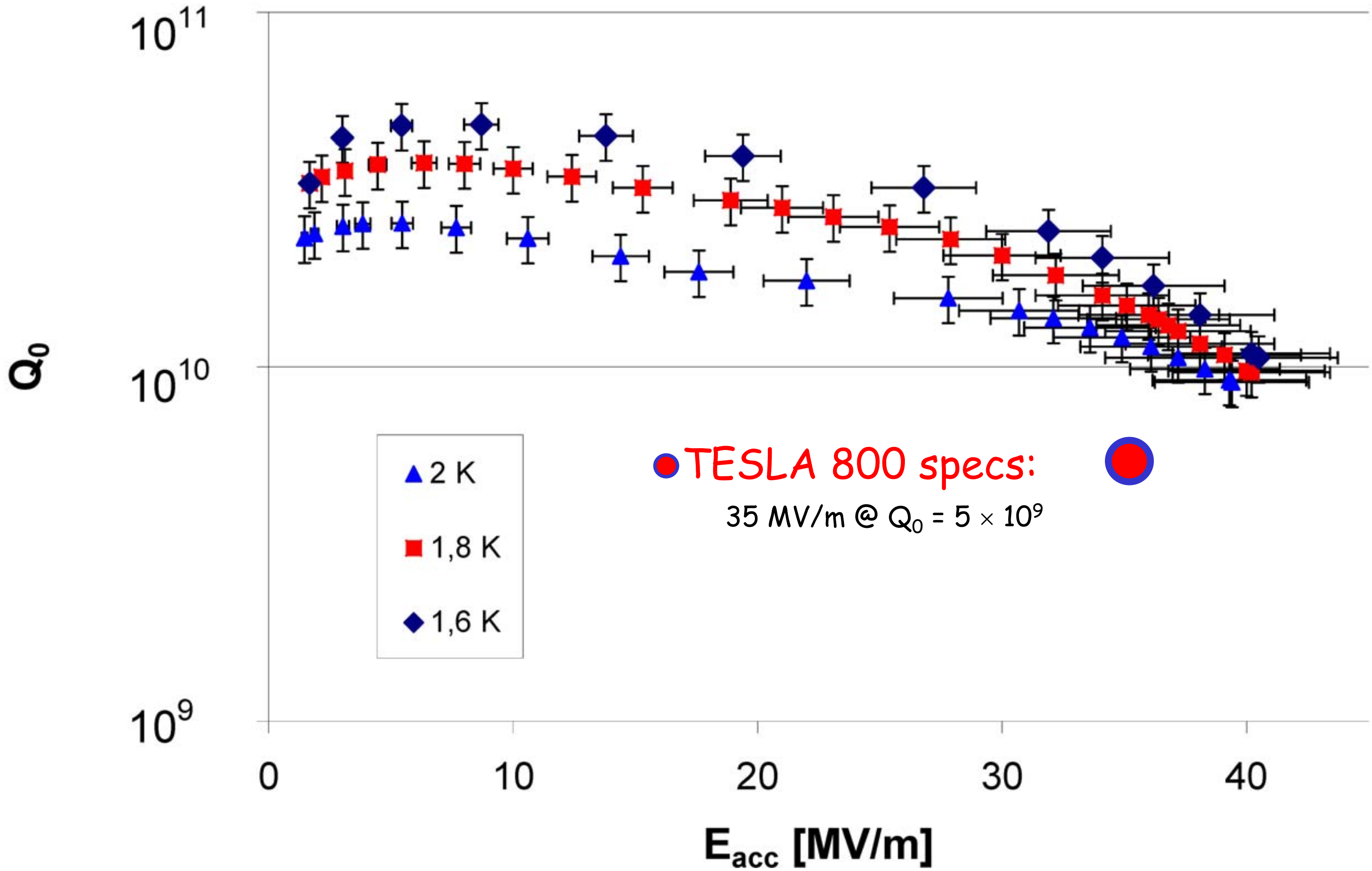
EP at the new DESY plan   800°C annealing   120°C Backing



Results on AC70 - 2

Very low residual resistance

Negligible Field Emission



Important results for TESLA LC

EP & 120°C backing are the key steps of the recipe

Field Emission and Q-drop cured

- Maximum **field is still slowly improving**
- Negligible Field Emission detected, that is
- **Negligible dark current expected** at this field level
- Cavity can be **operated close to its quench limit**
- Induced **quenches are not affecting cavity** performances

TESLA

String Assembly

The assembly of a string of 8 cavities

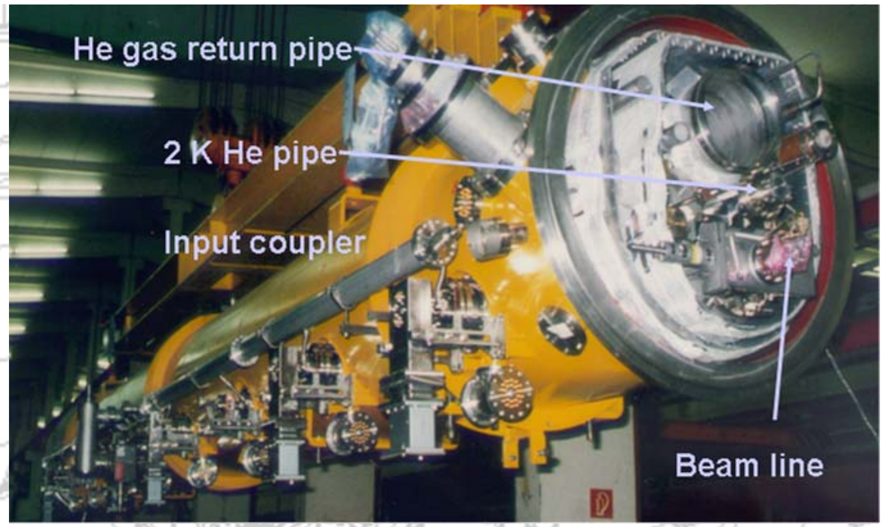
- is a standard procedure
- is done by technicians from the TESLA Collaboration
- is well documented using the cavity database as well as an Engineering Data Management System
- was the basis for two industrial studies.

We are ready to transfer this well known and complete procedure to industry.

The inter-cavity connection is done in class 10 cleanrooms

Performing Cryomodules

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

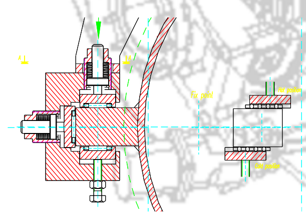


Cryomodule Characteristics

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

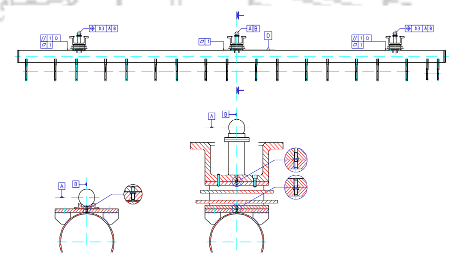
Required plug power < **6 kW**

Sliding Fixtures @ 2 K



"Finger Welded" Shields

Reliable Alignment Strategy

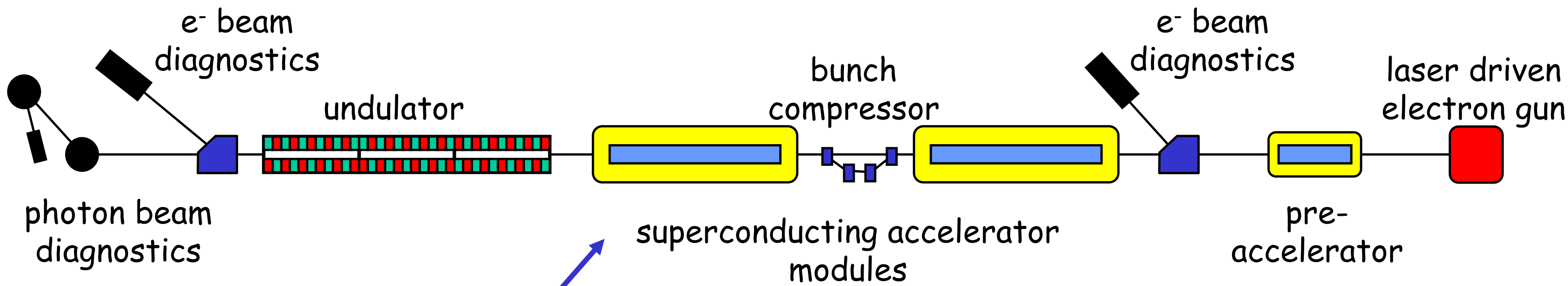


Module Assembly

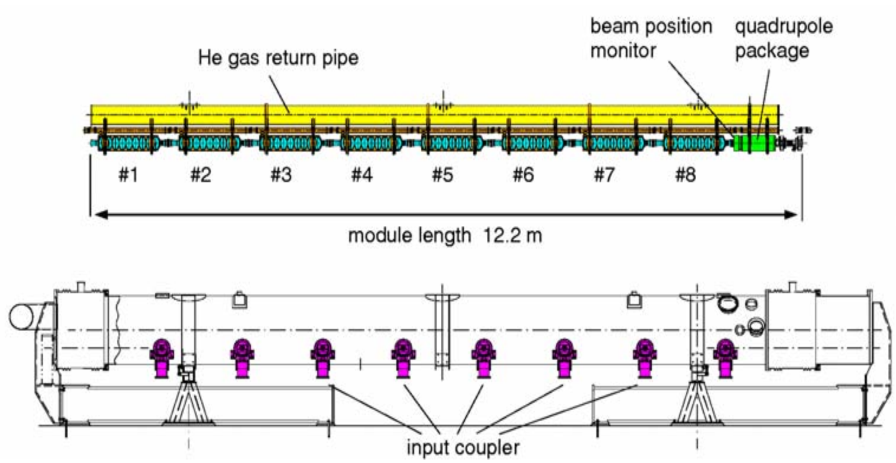
The module assembly is a well defined and standard procedure.

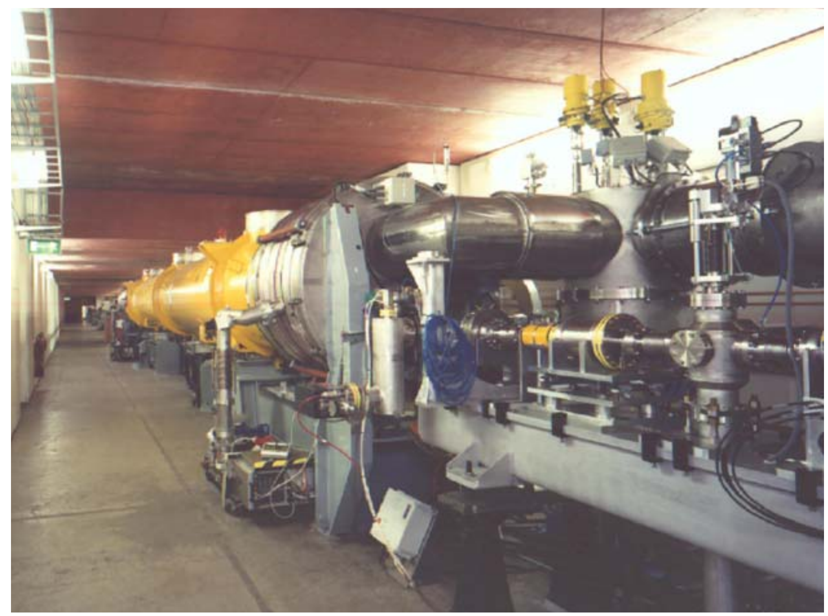
- experience of 10 modules exists
- the latest generation (type III) will be used for series production (XFEL requires 120 modules)
- several cryogenic cycles as well as long time operation were studied
- the assembly problems occurred are well understood and cured

The TTF I Linac - 6 Year exp.

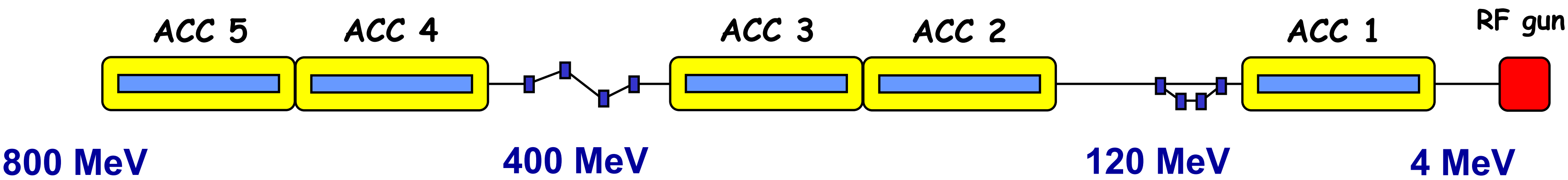


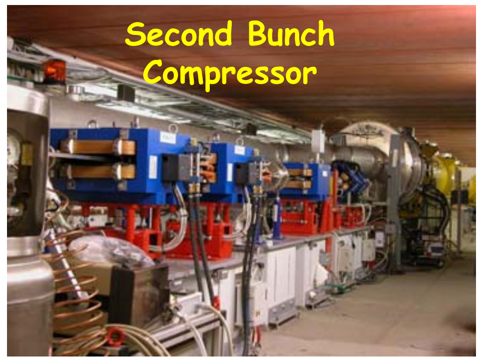
240 MeV **120 MeV** **16 MeV** **4 MeV**





TTF II under Commissioning



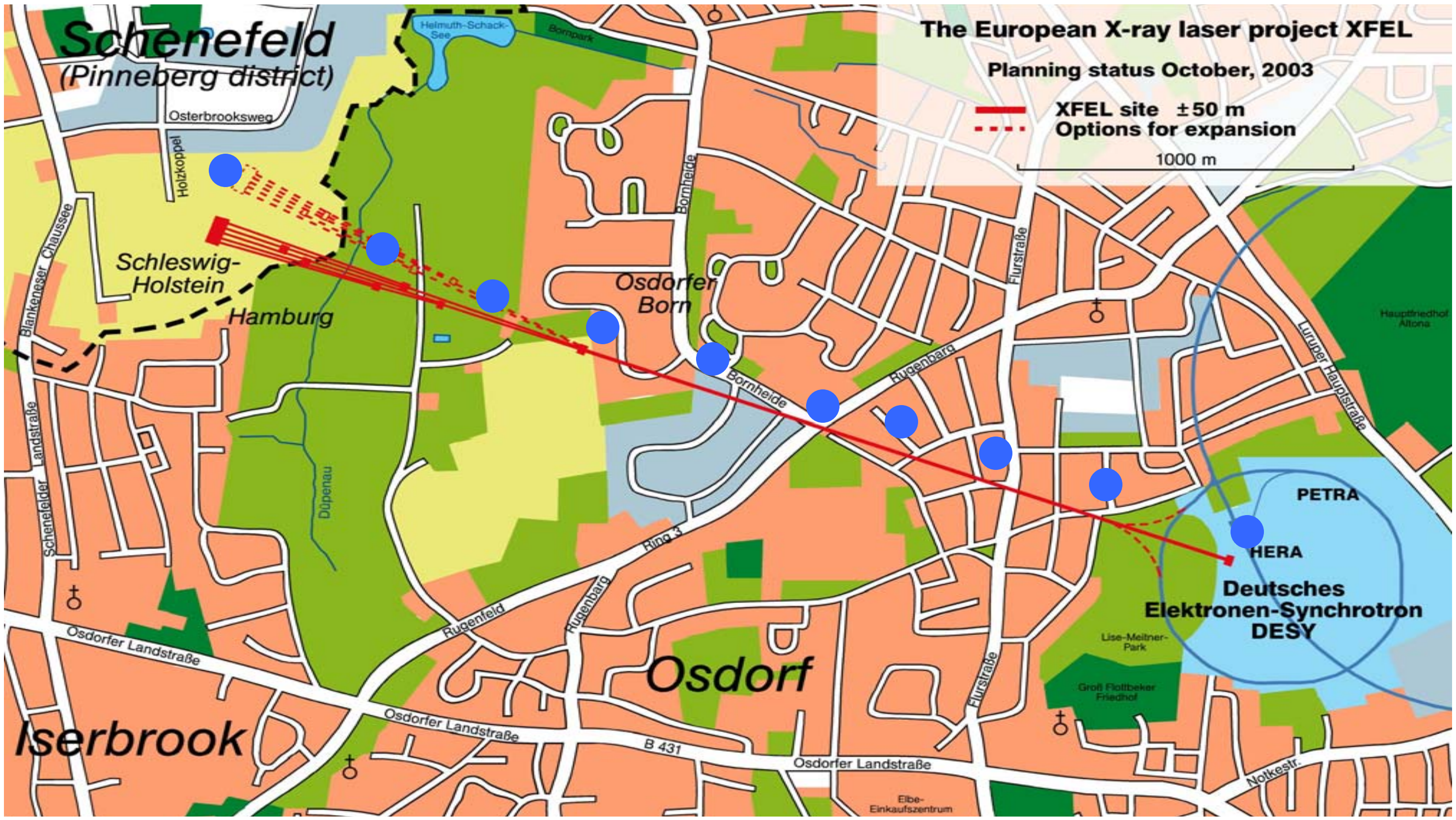


VUV FEL User Facility

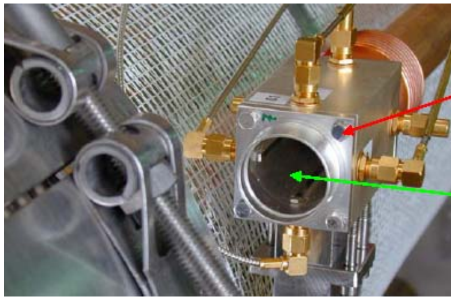
- Linac Commissioning under way
- SASE FEL Commisssioning by September this year

X-FEL coming soon

- 50% funded by the German Government - European consensus growing
- Great opportunity for TESLA
  - Machine reliability according to SRL standards
  - Industrial mass production of cavities (~ 1000) and modules (> 120)

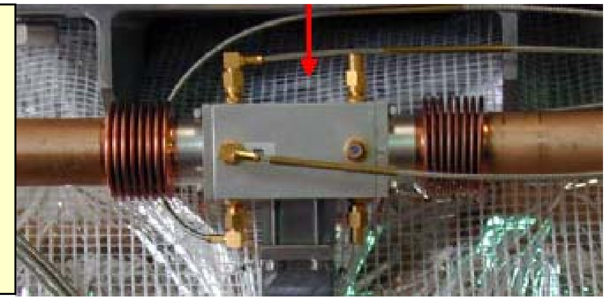


Cavity and Module Alignment

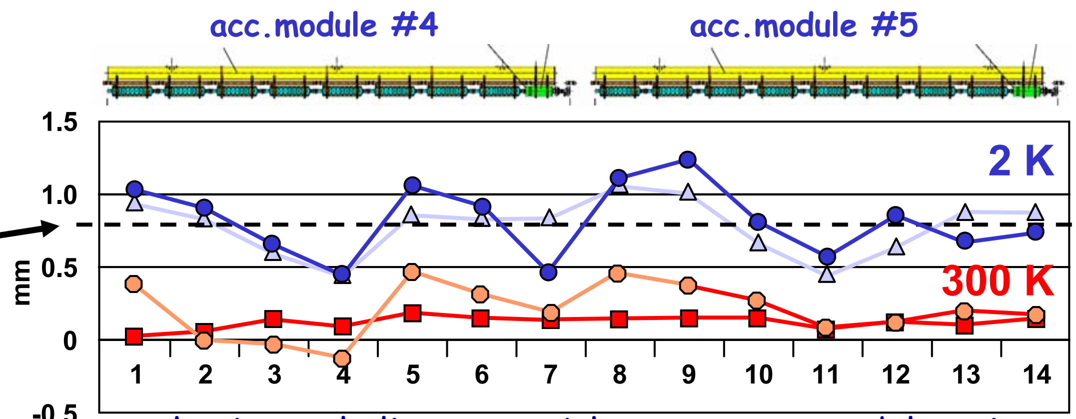


cavity / quad string alignment is measured using a stretched wire system

at warm and at cold temperature



corresponds to a perfectly aligned cavity / quad string



horizontal alignment with respect to module axis

20-Jun-03	300 K	
22-Jul-03	2 K	
06-Oct-03	300 K	
31-Mar-04	2 K	

TDR specifications (rms):

cavities	x/y:	+/- 0.5 mm
	z:	+/- 1 mm
quad/dip	x/y:	+/- 0.3 mm
	z:	+/- 1 mm
	roll:	+/- 0.1 mrad

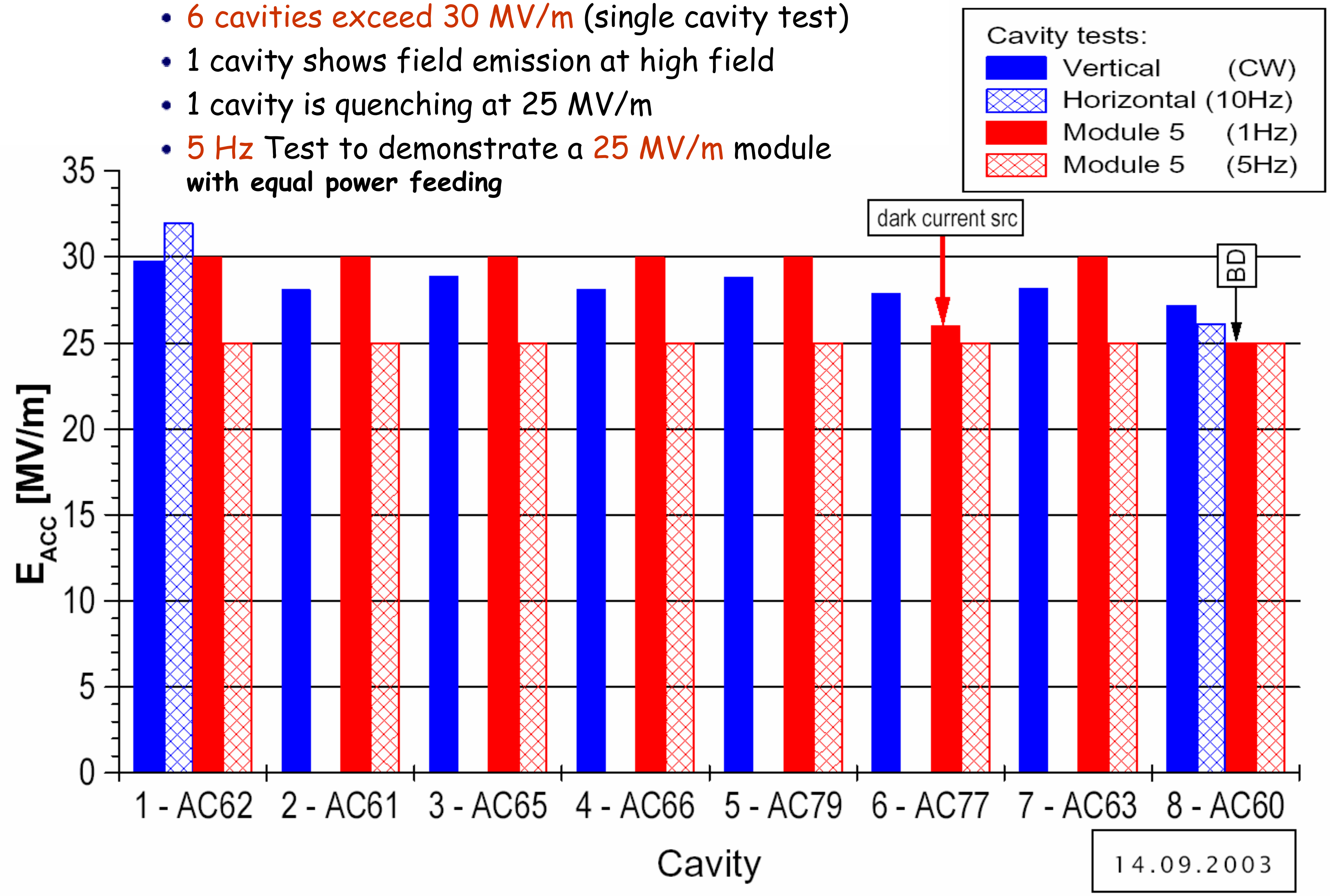
Results (peak):

cavities	x:	+/- 0.35 mm
	y:	+/- 0.25 mm
quad/dip	x:	+ 0.1 / - 0.4 mm
	y:	+ 0.2 / - 0.5 mm
overall module tilt		≈ 0.1 mrad

RF results in module # 5

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

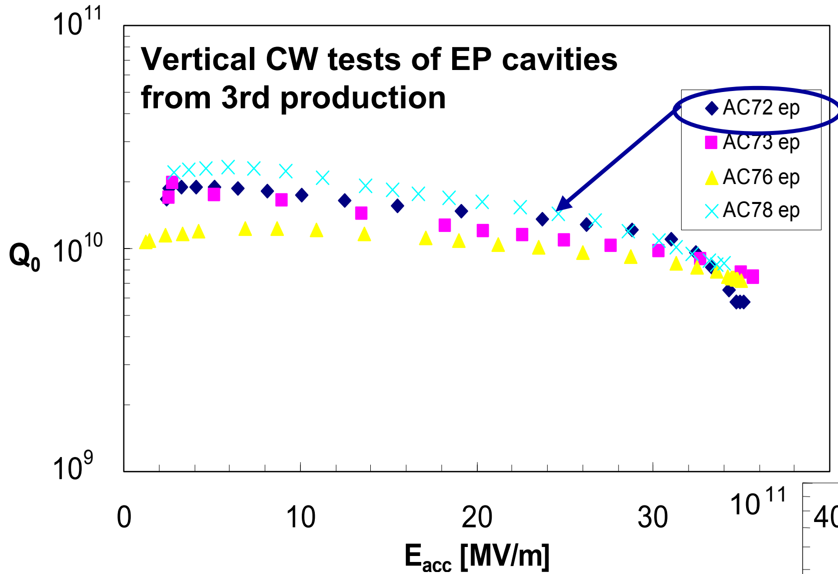


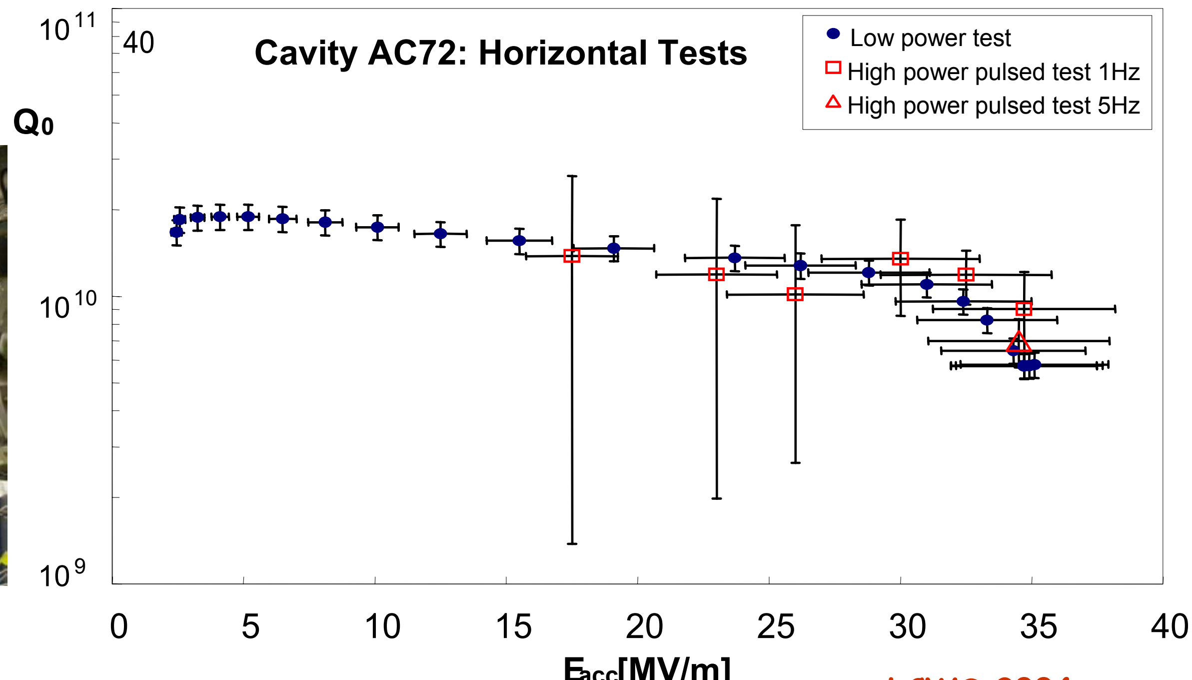
Cavity Program for TESLA & X-FEL

- **Industry is being producing 30 new cavities** for extensive tests
- Cavity delivery will start end of May
- **Cavities will follow the standard preparation procedure** at DESY to further define protocols for industry. This includes:
  - 800 °C annealing, no 1400 °C firing is foreseen
  - ElectroPolishing (EP)
  - High Pressure Rinsing (HPR)
  - Clean Room handling and assembling
- Because of conflict with TTF II operation as VUV-FEL test Facility a Module test stand has been designed and will be in operation by 2005. **The 35 MV/m module test is expected by end 2005**.
- Meanwhile **tests of fully equipped cavities will continue into the horizontal cryostat "Chechia".**
- **The worst of the 35 MV/m cavities has been scarified for a test in module ACC 1**, which will be operated in the VUV-FEL Test Facility with an accelerating voltage below 20 MV/m (Injector issues)

TESLA

EP Cavity Test inside a Module

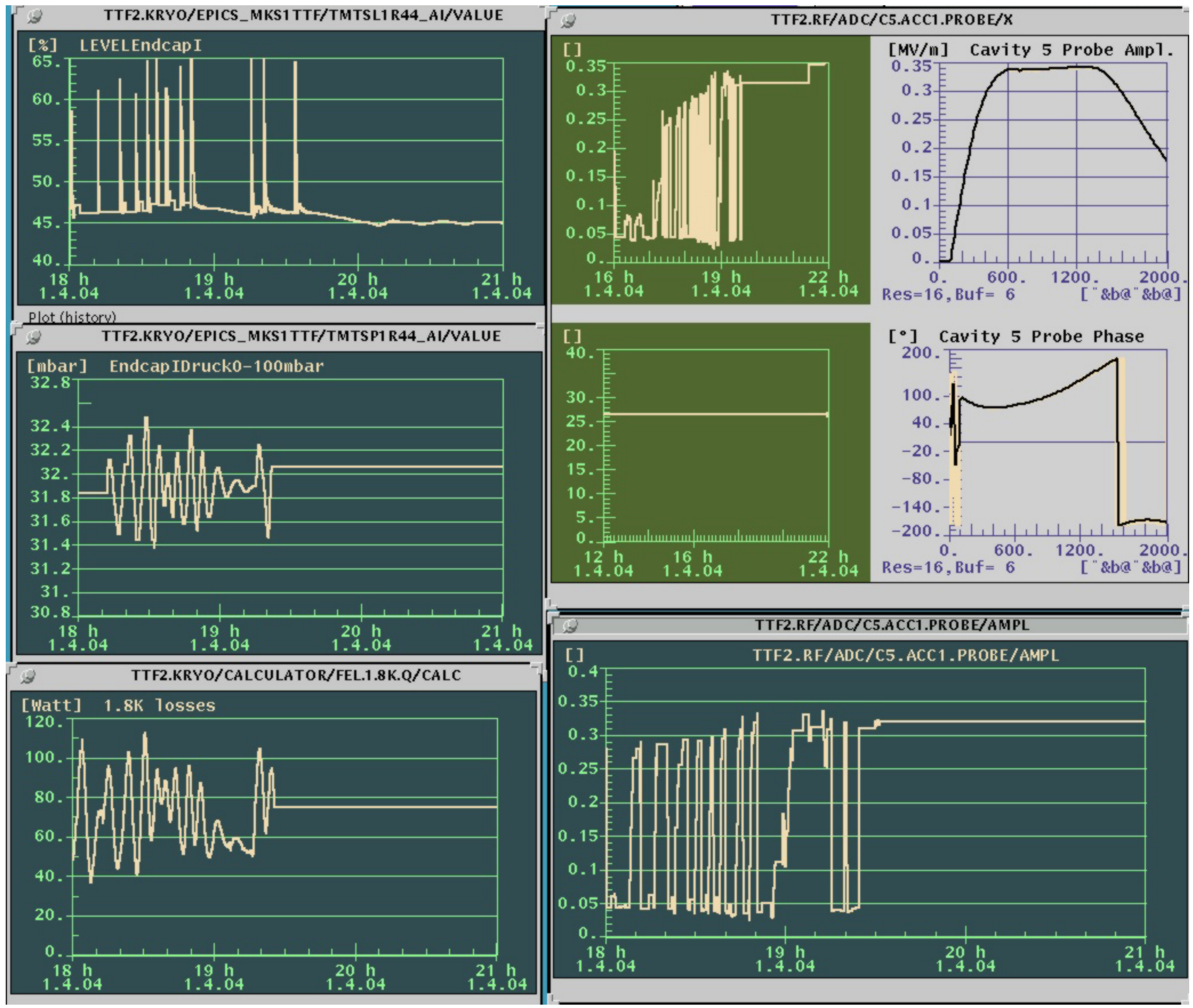




TESLA

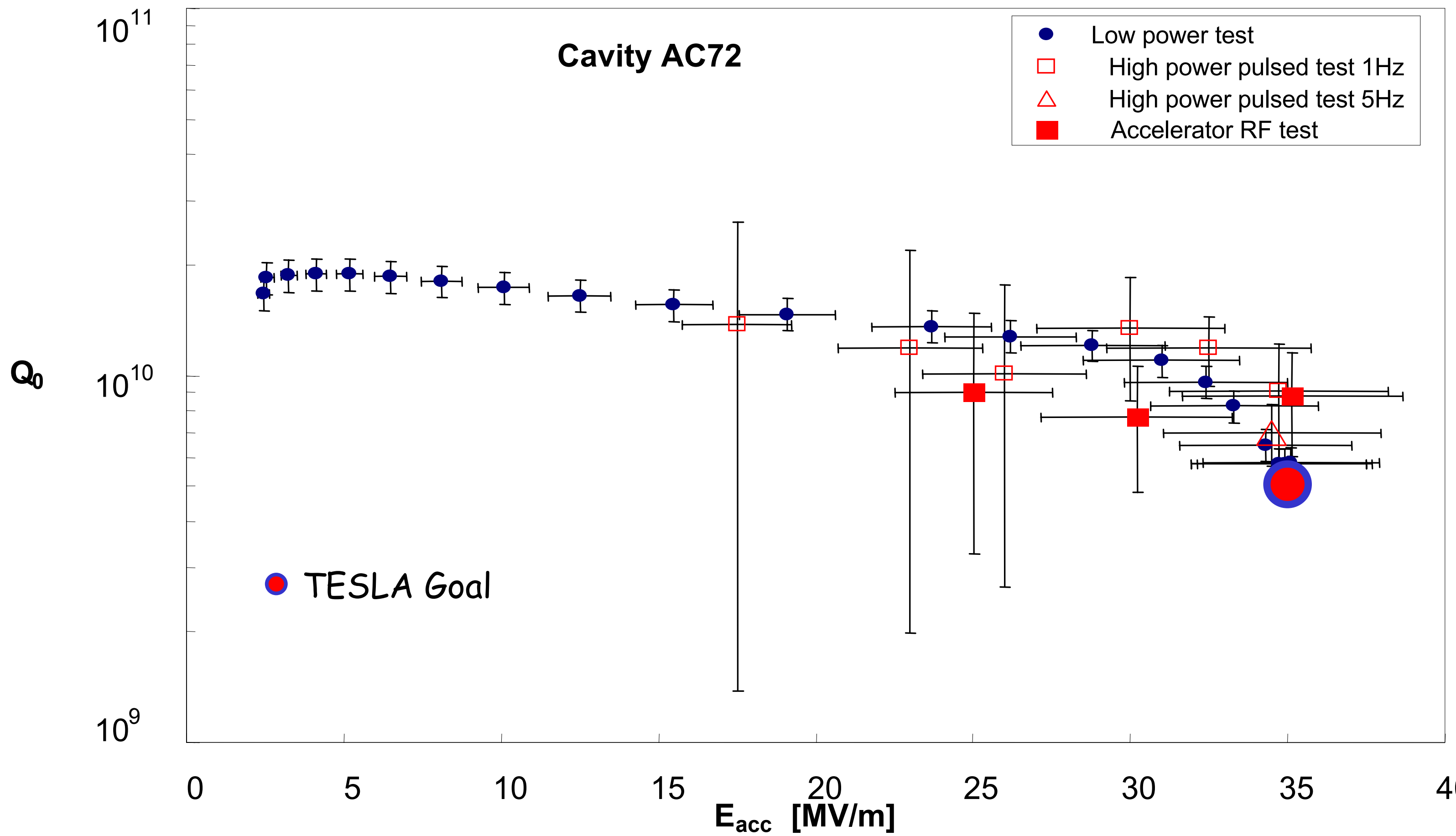
April 1^{st} 2004

- Very fast conditioning of cavity and coupler
- Full pulse length (800 µs flat top) and 5 Hz repetition rate easily achieved
- Quenches easily detected and recovered
- With just feedforward for Lorentz force detuning compensation AC 72 was stably operated for several hours
- Feedback successfully tested



AC72 inside ACC1 Results

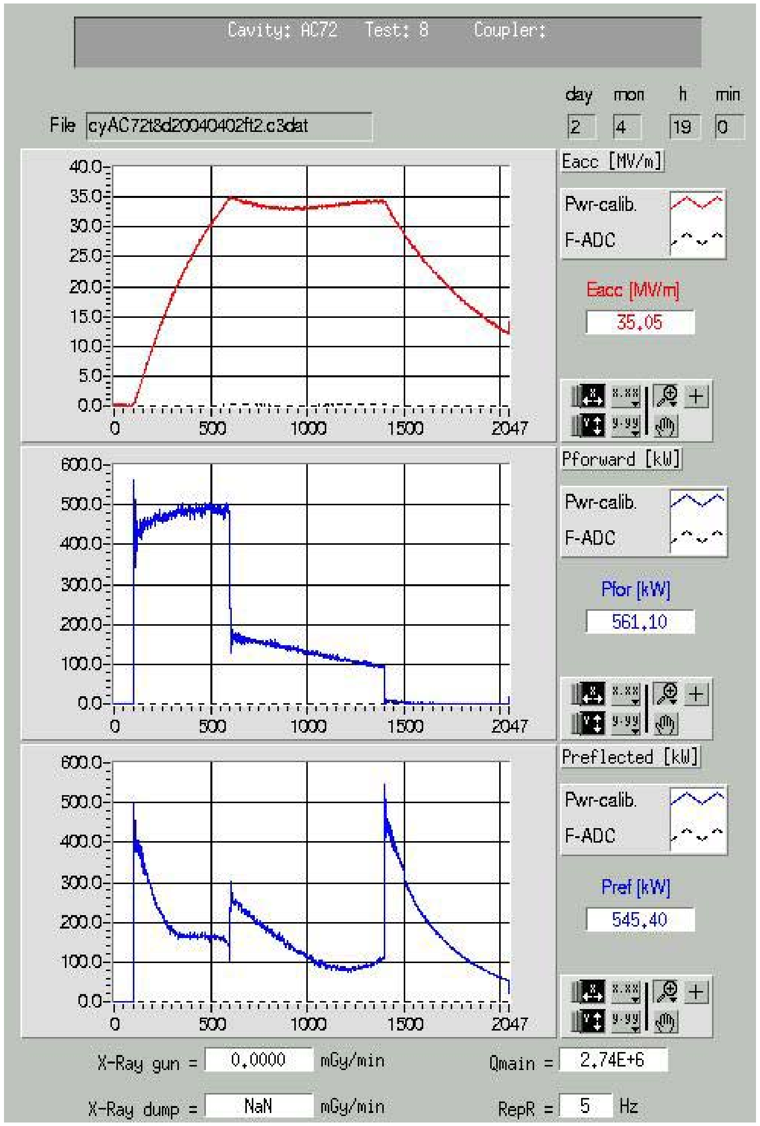
- **No field degradation from Vertical, Horizontal, Module and Beam**
- No radiation detected up to 35 MV/m. Negligible field emission and dark current



Summary of AC72 Test in ACC1

- One of the Electropolished cavities (AC72) was installed into the module ACC 1 for the VUV-FEL
- Cooldown of the LINAC finished on March 31st
- Cavity was individually tested in the accelerator with high power RF
- **Result:**

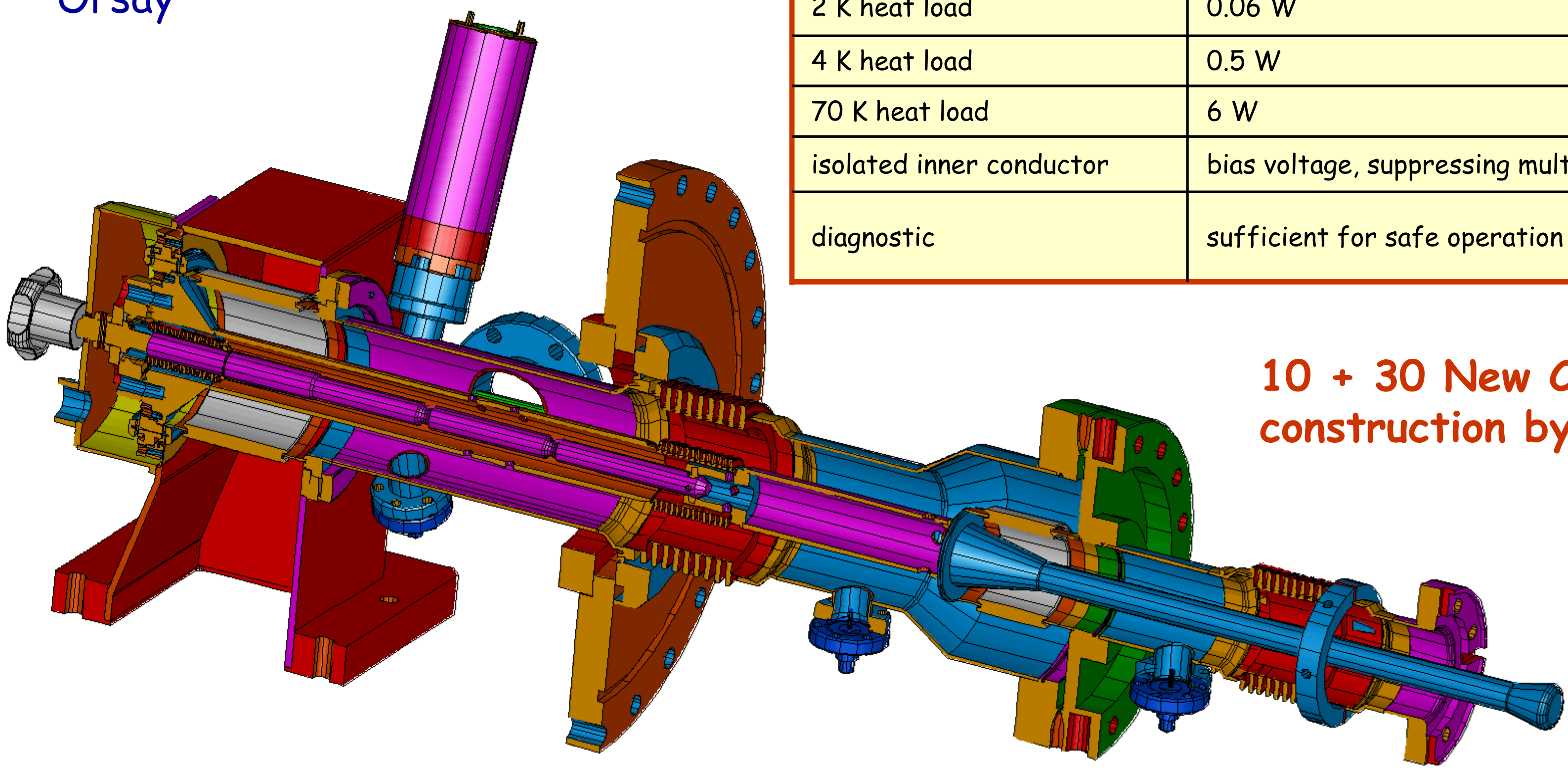
  35 MV/m in the accelerator!
- Calibration has been confirmed with beam and spectrometer
- No field emission detected
- Preliminary good results with LLRF and Piezo-tuner
- No degradation, neither the cavity nor the coupler, as is expected for SRF cavities.



The TESLA Coupler: TTF III

- TTF III Coupler has a robust and reliable design.
- Extensively power tested with significant margin
- New Coupler Test Stand at LAL, Orsay

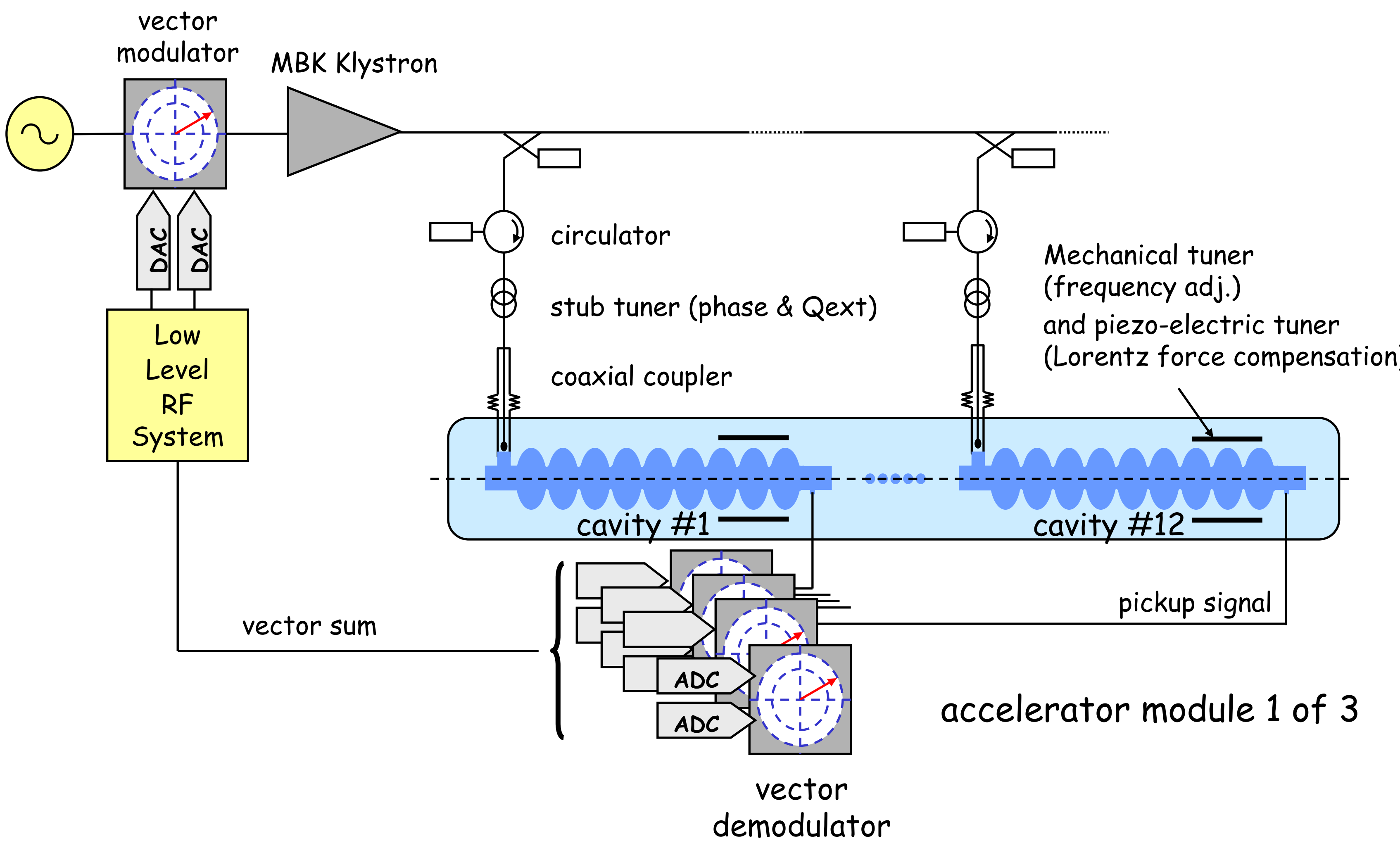
frequency	1.3 GHz
operation	pulsed: 500 µsec rise time, 800 µsec flat top with beam
two windows, TiN coated	• safe operation • clean cavity assembly for high Eacc
2 K heat load	0.06 W
4 K heat load	0.5 W
70 K heat load	6 W
isolated inner conductor	bias voltage, suppressing multipacting
diagnostic	sufficient for safe operation and monitoring



10 + 30 New Couplers in construction by industry

THE TESLA RF Unit

1 klystron for 3 accelerating modules, 12 nine-cell cavities each



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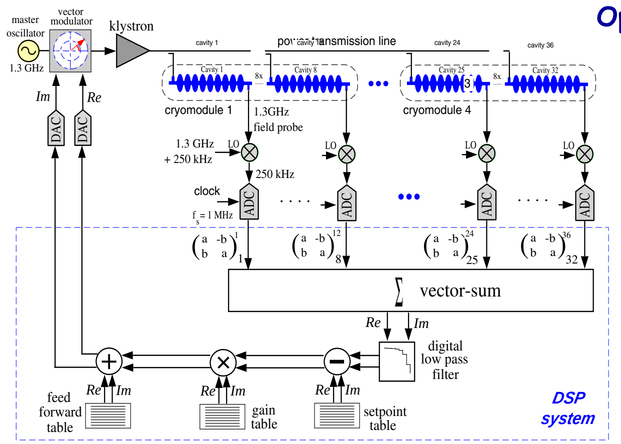
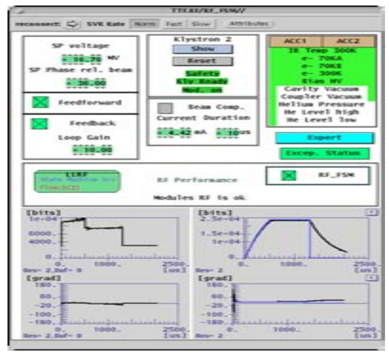
LLRF performance in TTF

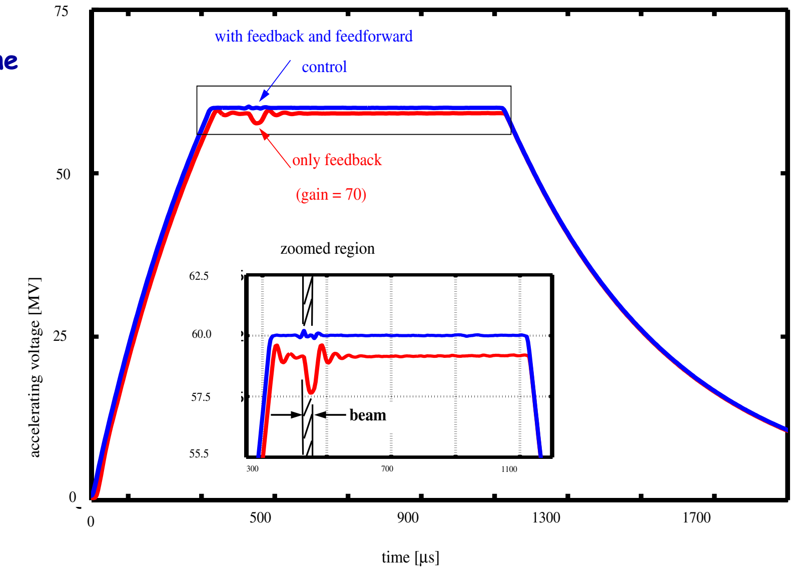
Principle of RF Control



Operation with Final State Machine



from TTF Console in Milano



Contributions to Energy Fluctuations

1. Lorentz Force
2. Microphonics
3. Bunch-to Bunch Charge Fluctuations
4. Calibration error of the vector-sum
5. Phase noise from master oscillator
6. Non-linearity of field detector
7. Klystron Saturation
8. RF curvature (finite bunch length)
9. Wakefield and HOMs

Microphonics

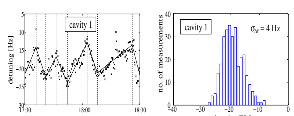


Figure 2: Fluctuations of the cavity resonance frequency. a) Slow drifts over a period of one hour and b) probability density of the cavity resonance frequency with an rms width of 2Hz - 7Hz.

Lorentz Force Detuning

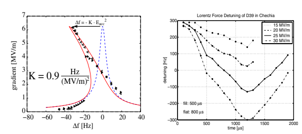
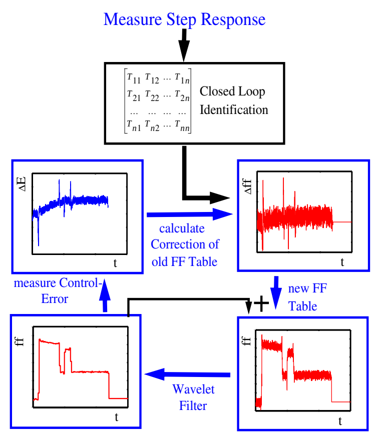


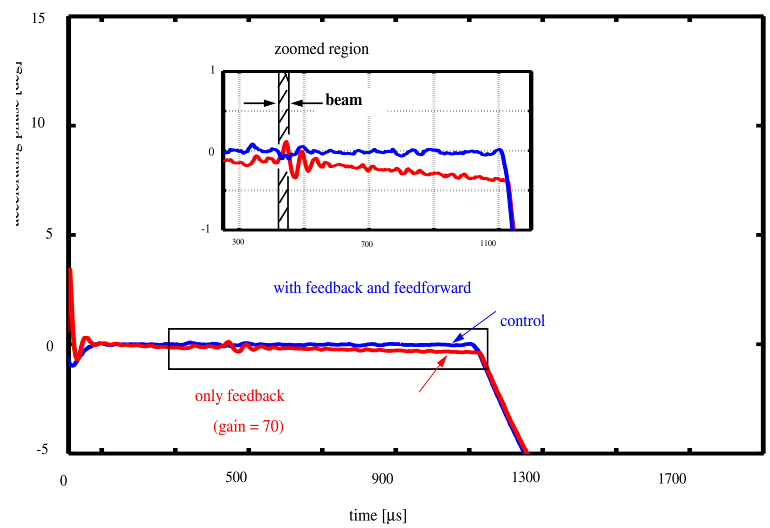
Figure 3: Influence of radiation pressure on the resonance curve of a sc cavity. a) Static detuning during cw operation and b) dynamical detuning during nominal TESLA pulse.

Adaptive Feedforward



Adaptive Feed Forward can handle nonlinear systems through linarisation around the operating point.

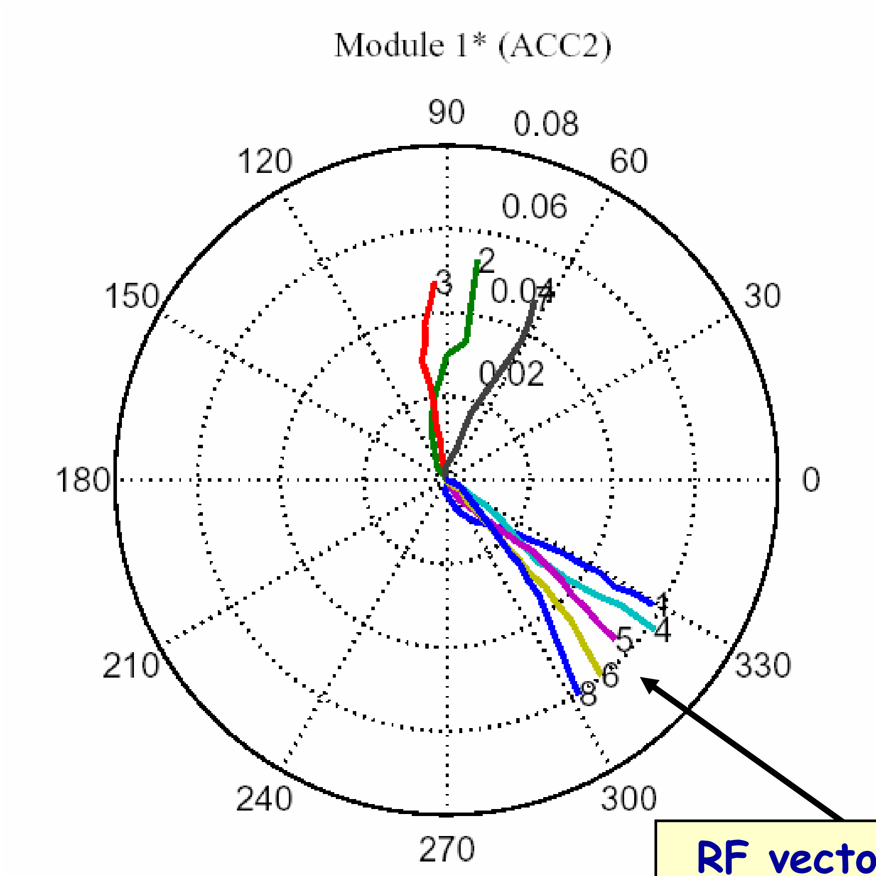
The calculation of a new feed forward table needs only a few seconds.



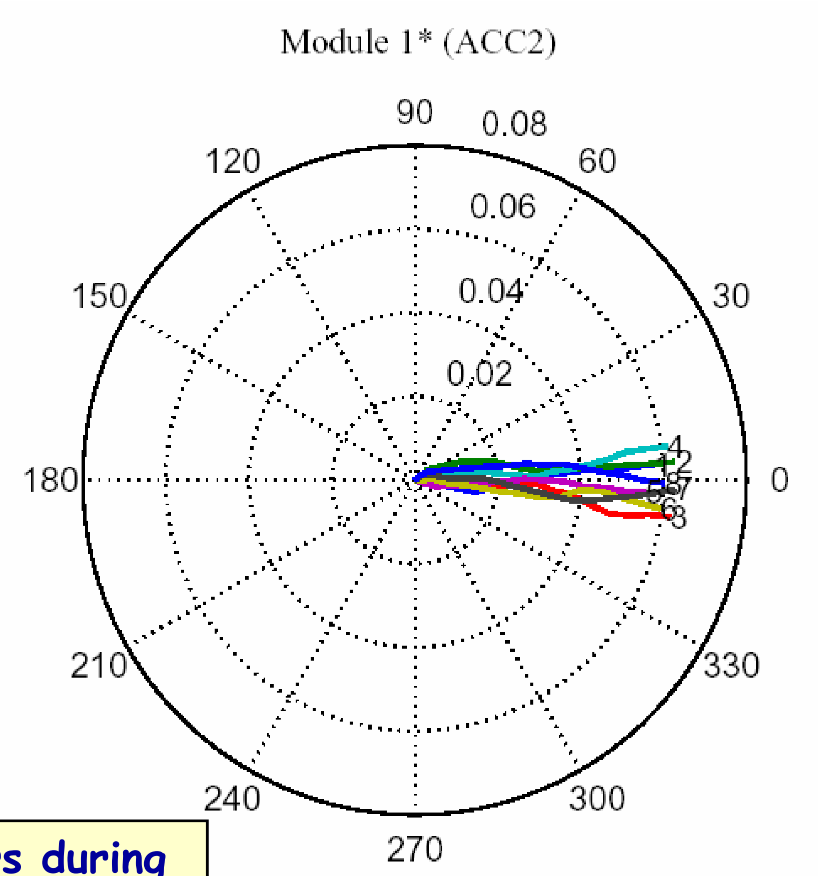
LLRF: Operation Example

Phase Adjustment Using Beam Transients

before adjustment



after adjustment

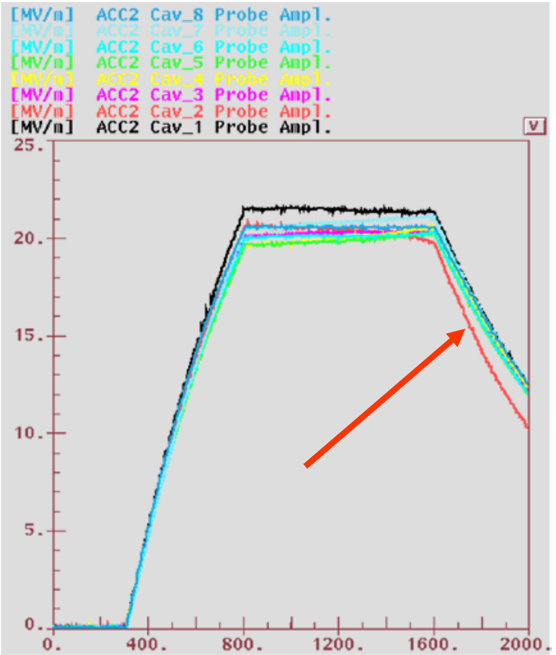


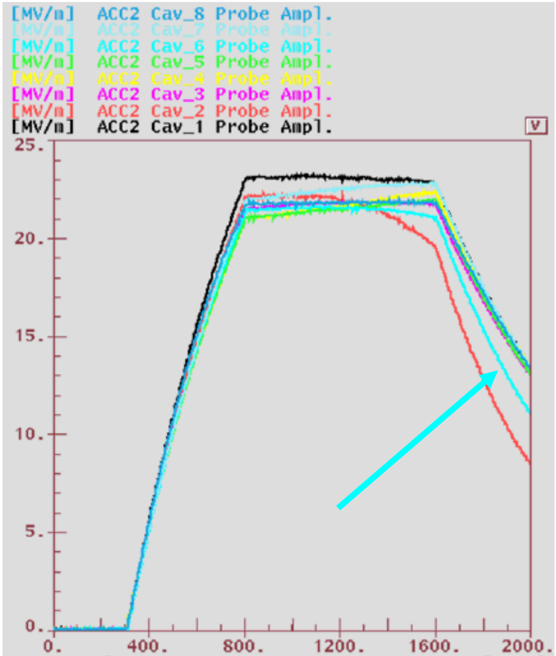
RF vectors during 800 μs flat top

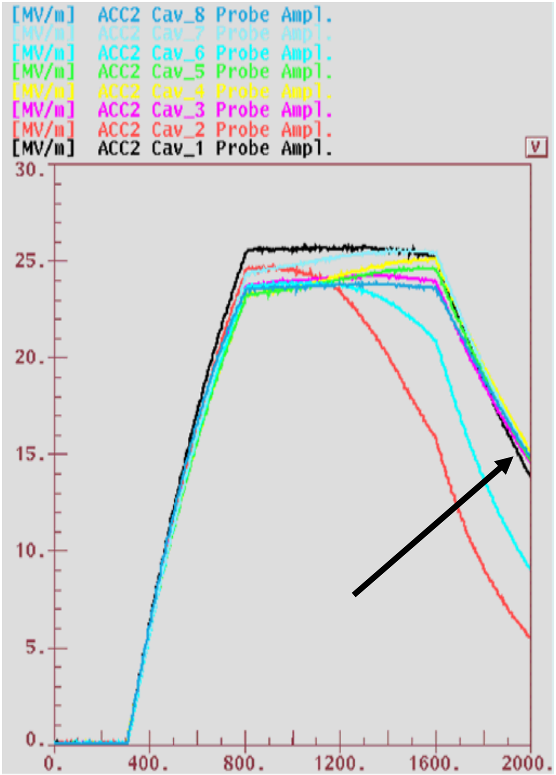
LLRF: Operation Example

Operation of a Module (# 1*) above its Quench limit

Cavity quench detection algorithms and exeption handling procedures analyze the probe signals...





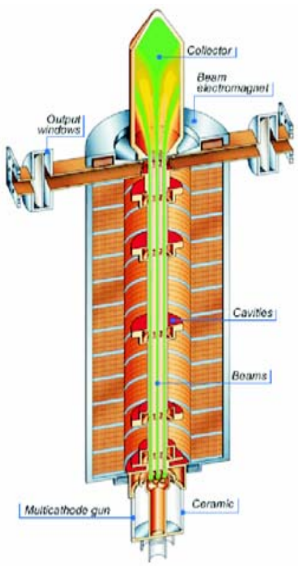


Stable Module #1* operation with slowly but steadily increased gradient

1st quench: **Cavity 2** E_{acc}=19 MV/m	2nd quench: **Cavity 6** E_{acc}=21 MV/m	3rd quench: **Cavity 1** E_{acc}=24 MV/m

TESLA Multi Beam Klystrons

Three **Thales** TH1801 Multi Beam Klystrons produced and tested



Achieved efficiency	65%
RF pulse width	1.5 ms
Repetition rate	5 Hz
Operation experience	> 5000 h

10% of operation time at full spec's

Indipendent beam design proposed and built by **CPI**. Tests just started.

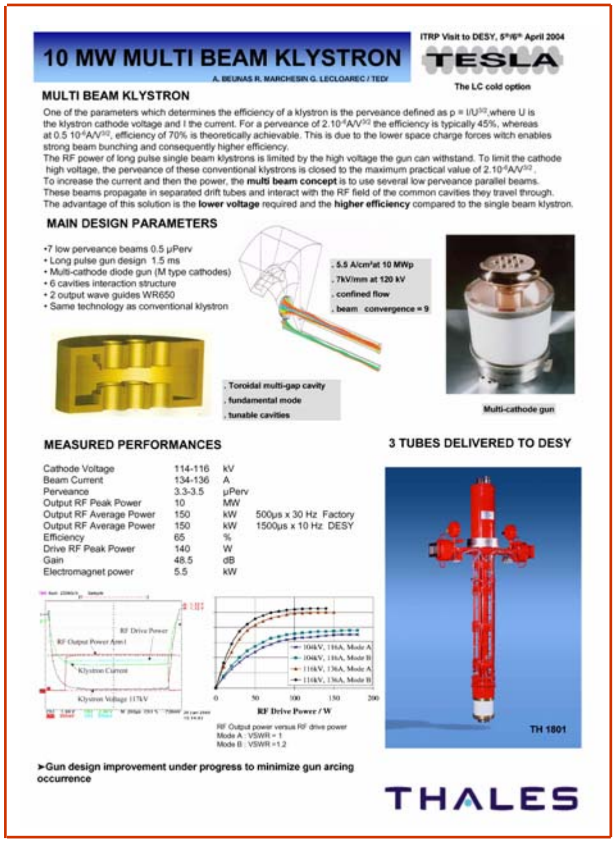
A new design proposed by Toshiba looks robust and should reach 75% efficiency

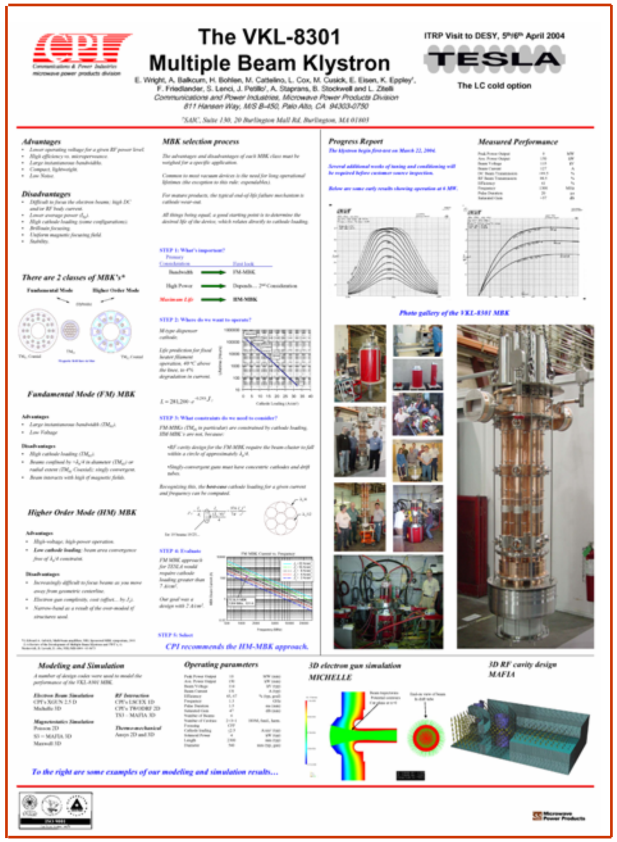
First prototype tests are starting - Cathode loading < 2.1 A/cm^2

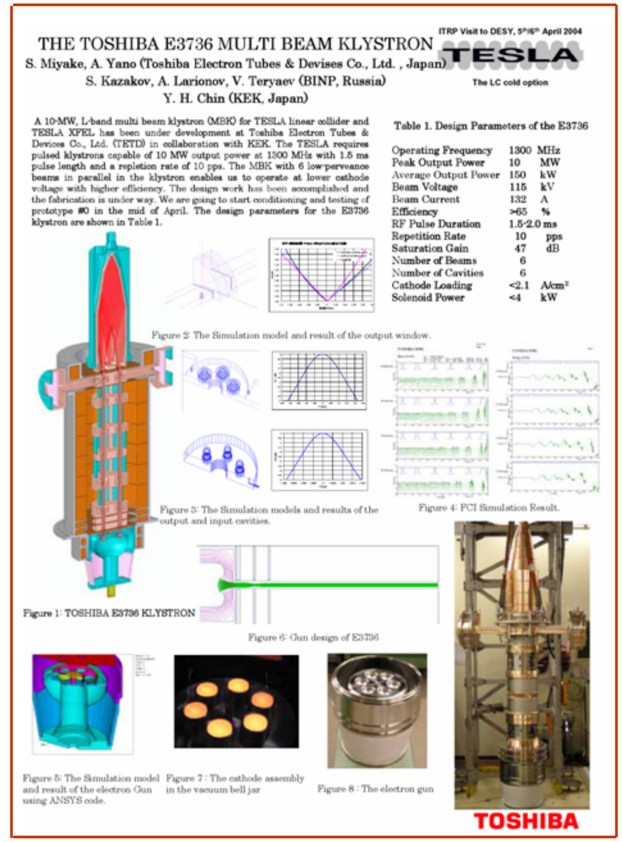
TESLA

TESLA Multi Beam Klystrons

The 3 major Klystron Industries are endorsed in the TESLA klys development
Design goals reached – MTBF ~ 100,000 hours expected (40,000 quoted in the TDR)







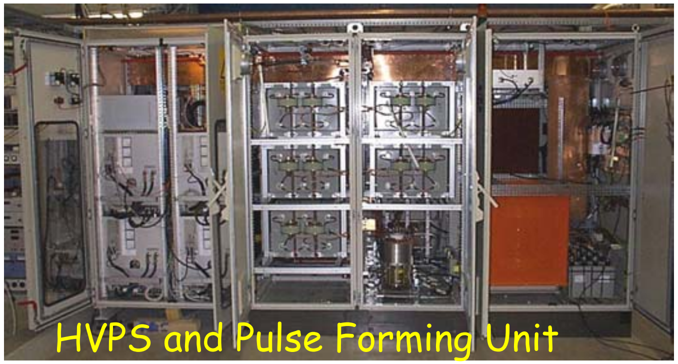
Representatives of: Thales, CPI and Toshiba participated with posters to the ITRP visit to DESY

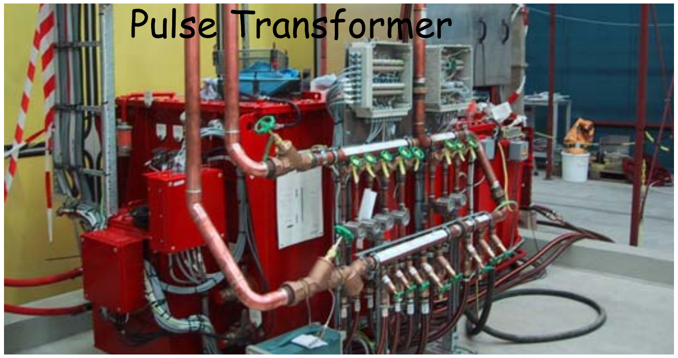
Modulators are not a concern

FNAL Modulator at TTF

- 10 Modulators have been built, 3 by FNAL and 7 by industry
- 7 modulators are in operation
- 10 years operation experience

- Work towards a more cost efficient and effective design started
- Hazardous components minimized
- Most components are standard
- Industry is ready to built turn key modulators fulfilling the specs





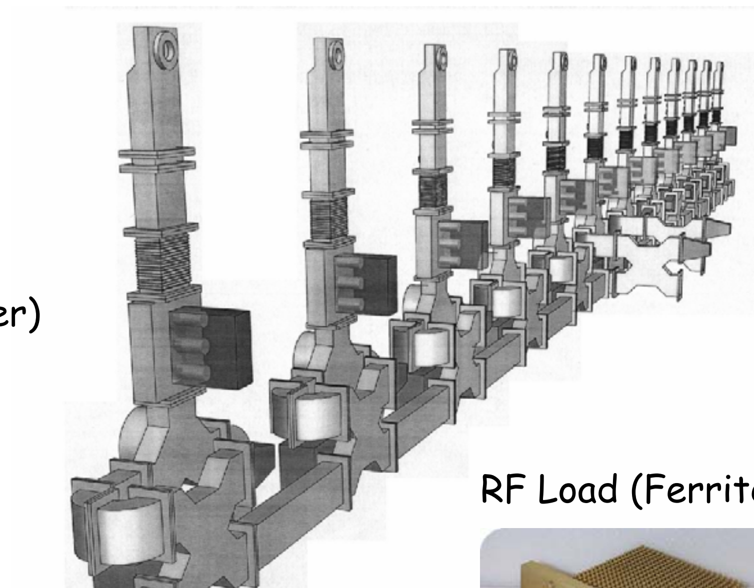
RF Waveguide Components

All standard components – Technology well established – Produced by Industry

3 Stub Tuner (IHEP, Bejing, China)

E and H Bends (Spinner)

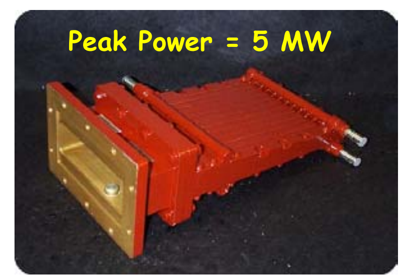
Circulator (Ferrite)



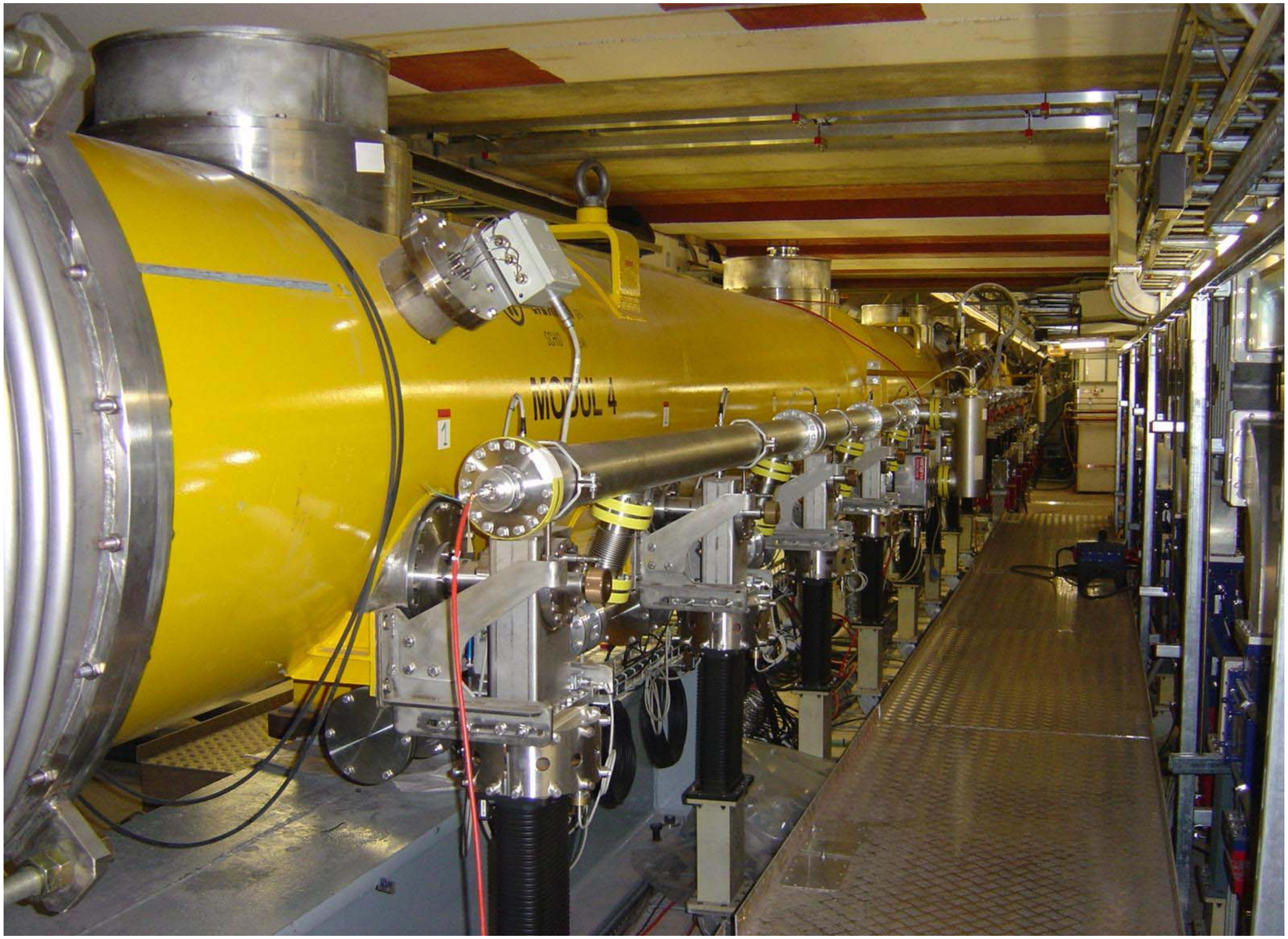
Hybrid Coupler (RFT, Spinner)

RF Load (Ferrite)

RF Load (Ferrite)



RF Distribution of Module # 4



TESLA

A Few Remarks

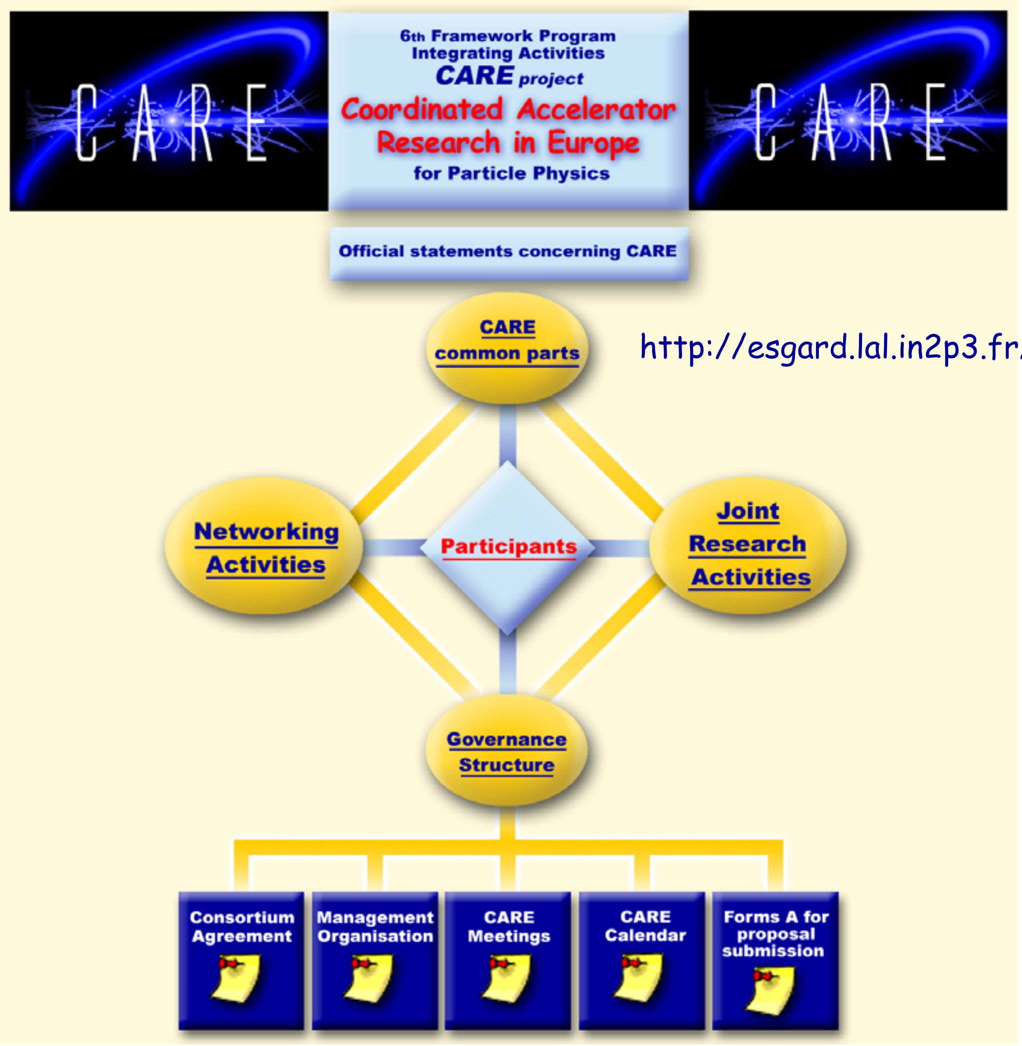
- Production of TESLA Cavities with accelerating field exceeding **35 MV/m has been proven.**
- All the previous limiting factors, including **Q-drop and dark current** have been **understood and cured**,
- TESLA Technology is widely distributed and on hands
- **Industry has already most of the required know-how** and technology transfer is under way.
- **The costing process for the TESLA TDR has been based on industrial studies** for mass production. All the fabrication steps have been analyzed and reviewed by industry.
- 16 major Industries participated with representatives and posters to the ITRP visit to DESY on April 5th.
- Detailed Engineering of major components for a further reduction of costs and improvement of component MTBF has started. On this subject **5 M€ have been allocated by EU on the framework of ESGARD/CARE**

ESGARD & CARE

ESGARD

European Steering Group on Accelerator R&D

(…) the directors of CCLRC, CERN, DAPNIA/CEA, DESY, LNF, Orsay/IN2P3, and PSI in consultation with ECFA have decided to form a **European Steering Group on Accelerator RD** (ESGARD), coordinated by Roy Aleksan with the administrative support of the CEA

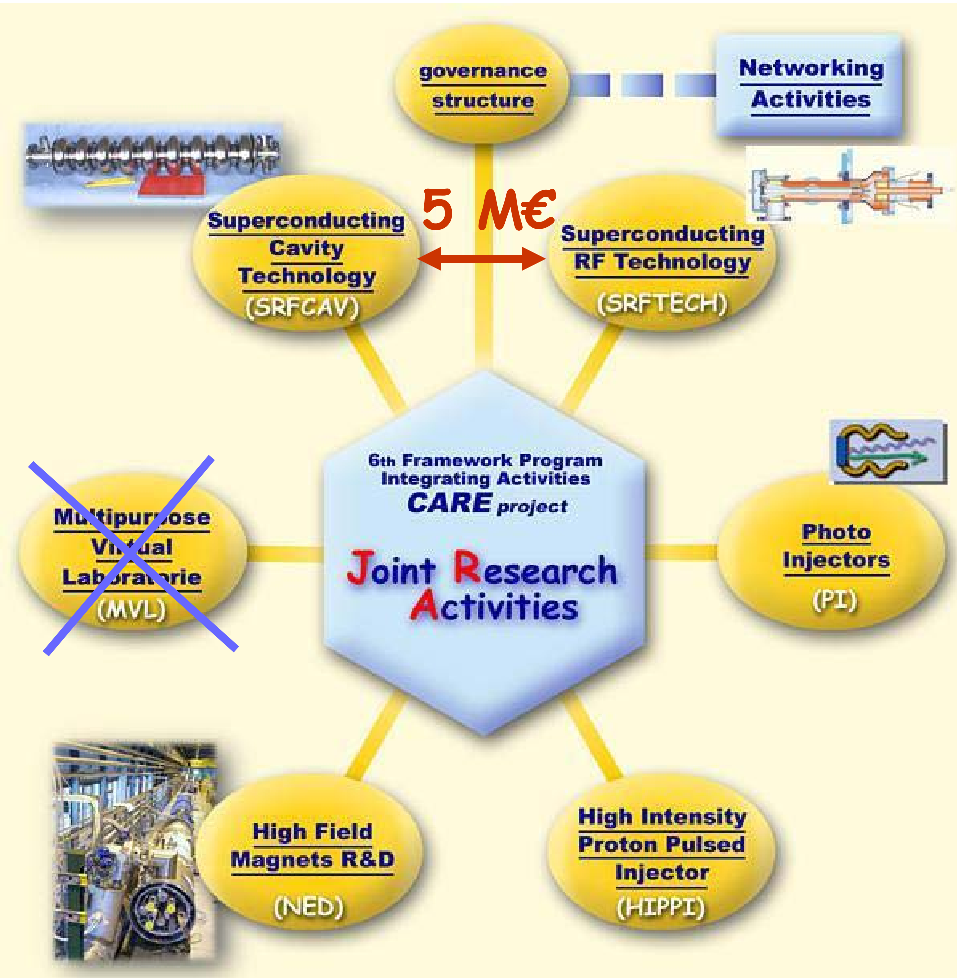


http://esgard.lal.in2p3.fr/

CARE

Coordinated Accelerator Research in Europe

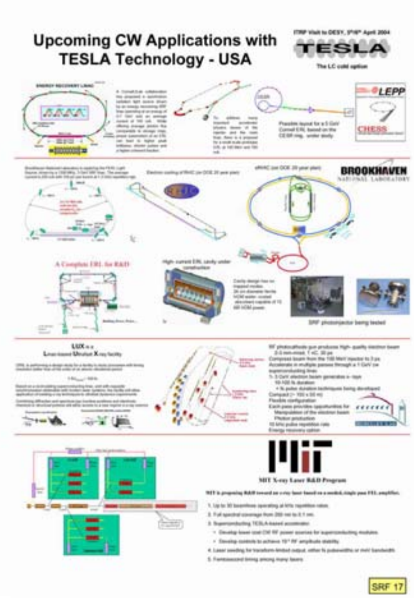
ECFA has given CARE a very high priority

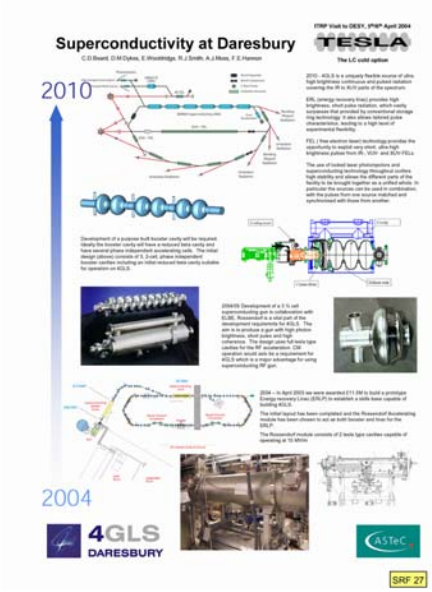


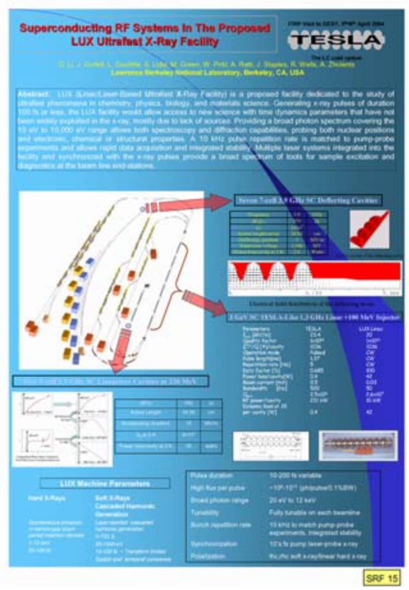
- The program was considered essential to:
  - particle physics, synchrotron light sources, high intensity protons and ion beam facilities and operation of accelerators
- Network activities approved on:
  - Electron linacs, neutrino beams and proton machines
- 4 Joint Research Activities approved on:
  - **Superconducting RF cavities, controls and ancillaries**
  - Photo Injectors for high charge and high brightness electrons
  - High Intensity Proton Pulsed Injectors
  - Next European Dipoles

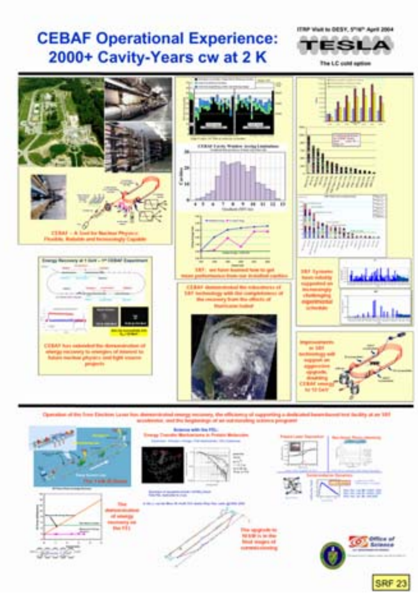
Projects and TESLA Technology

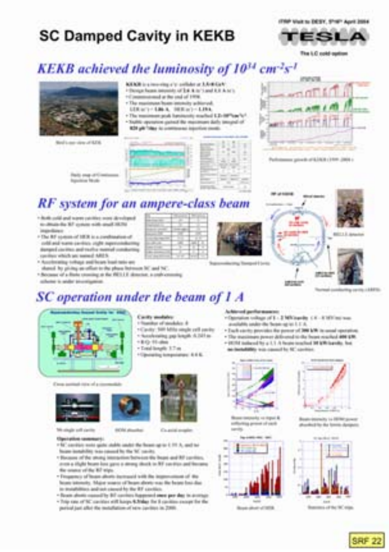
A Few Examples





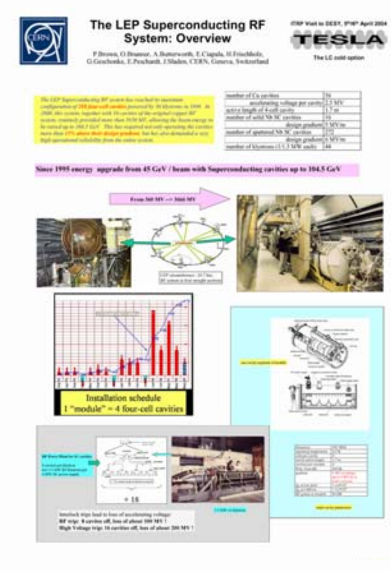


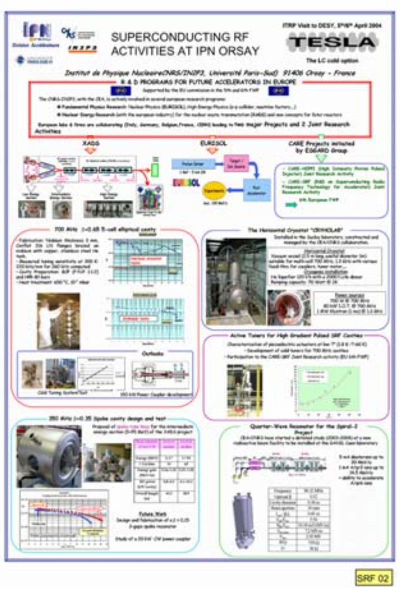


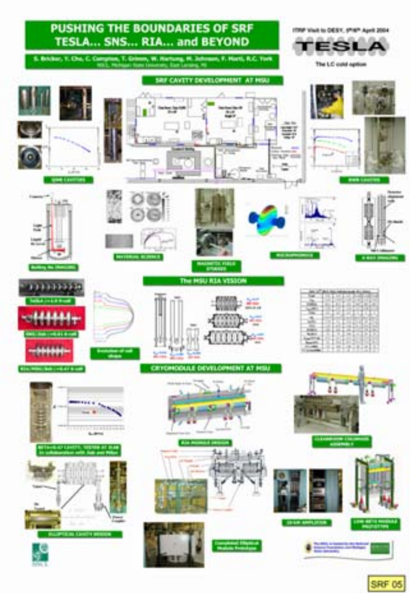


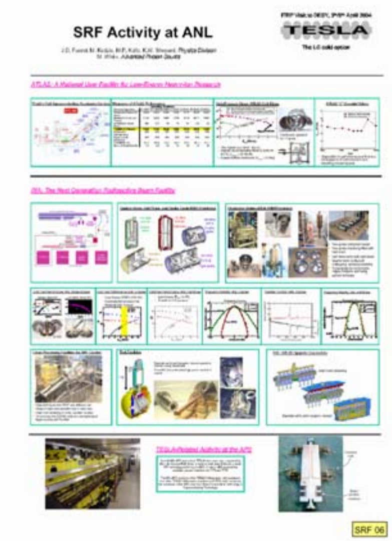
Distribution of TESLA Technology

A Few Examples









Future of TESLA Technology - 1

- 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 to demonstrate the feasibility of a TeV linear collider based on SRF has been the driving force in the past ten years to reach a new level of understanding of the past limiting factors.
- The concrete possibility of building a 30 Km linear collider convinced industry to invest for higher quality niobium material and for a complete understanding of the fabrication process at an industrial large scale.
- At present the SRF technology is considered in hand and industry is producing turn-key reliable systems that include SRF cavities and cryo-ancillaries.

Future of TESLA Technology -2

- A number of SRF infrastructures, sustained by expert people, are distributed worldwide. Their outcomes are still dominated by the past experience and their control on all the critical process parameters is not fully satisfactory. A large global SRF based project would update this distributed expertise, opening the way for further applications.

- Once all the design and fabrication steps are fully under control, for cavities, ancillaries and cryomodules, **an SRF system is a cheap and reliable transformer that, with more than 50% efficiency at relativistic energies, can convert plug to beam power**. And it can do so with high duty factor, representing a near-DC current source.

- That means that many applications beyond fundamental science can be conceived, ranging from **nuclear waste transmutations** to the industrial production of **photon beams** for **electronics, food or chemistry**.

Conclusions

- **TESLA Technology** has been developed and **is now ready** to be chosen as the basic technology **for the Global Linear Collider**.
- **Industry is ready** to produce all the major components at a well **defined cost** and with a well **defined reliability**.
- Should the Technology recommendation being for Cold, **margins** have been already recognized both
  - to improve performances (as new cavity shape for > 40 MV/m)
  - to reduce cost
- **The European X-FEL to be built at DESY** will represent the first large scale application among the many proposed that are 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 going to be built**.