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

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

Lecture 4

# The Cold Technology and the TESLA TDR

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INFN Milano and DESY
On leave from University of Milano

# The TESLA Mission

## Develop SRF Technology for the future Linear Collider

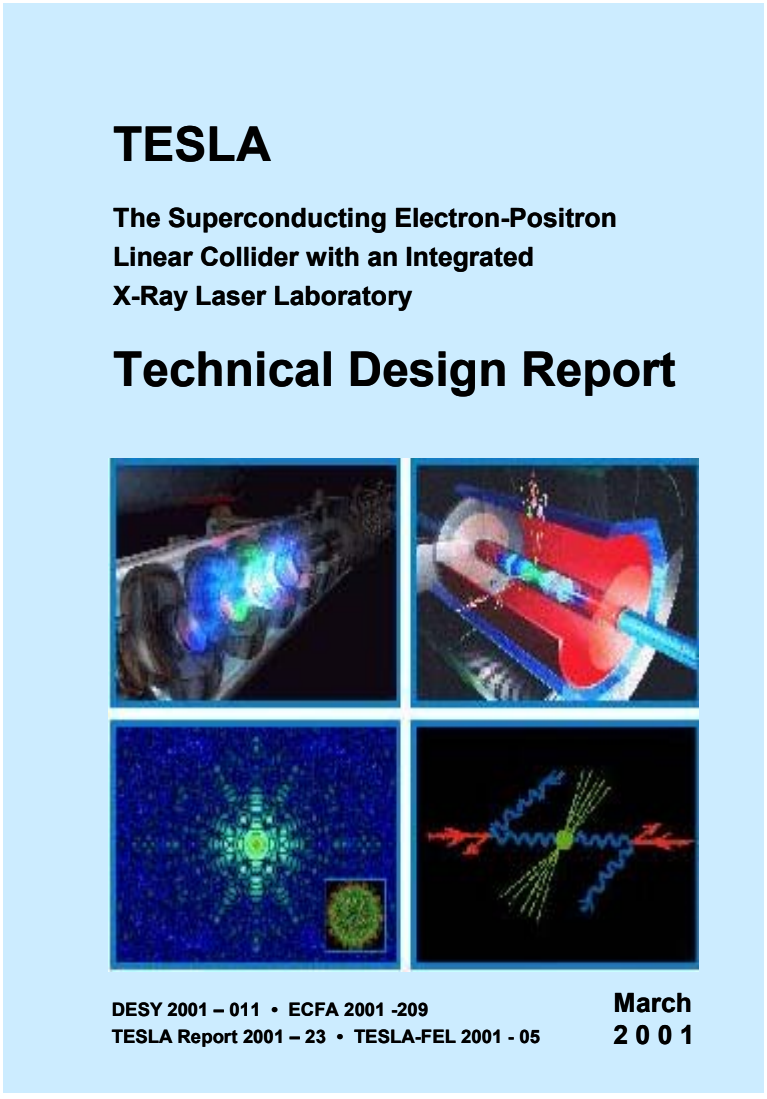
### Basic goals on SRF Technology

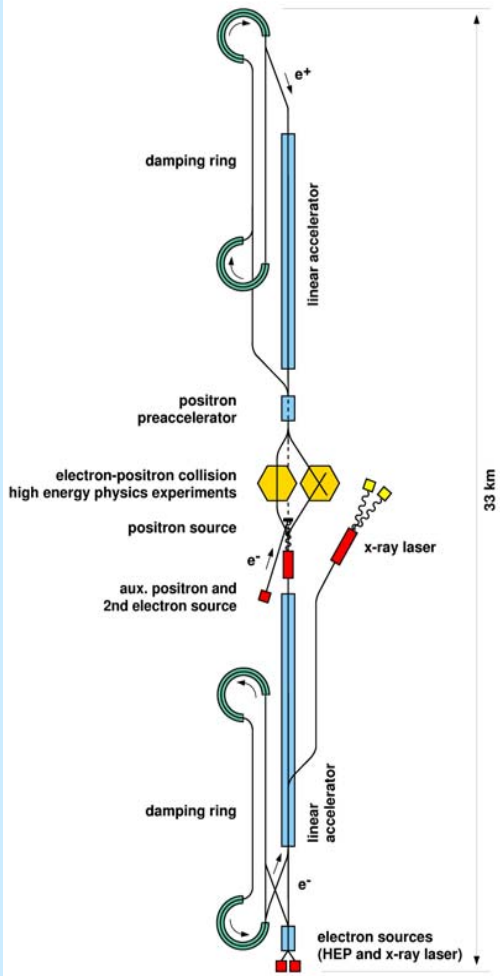
- **Increase gradient by a factor of 5: from 5 to 25 MV/m** (Physical magnetic field limit for Nb is ~ 180 mT)
  - Push cavity performances close to the physical limit, understanding practical limits
  - Set all the required quality control for reproducibility and industrial production
- **Make possible pulsed operation: Lorentz force detuning**
  - Combine SRF and mechanical engineering in cavity design
  - Develop efficient Modulators and Klystrons
  - Develop slow and fast tuners
  - Develop appropriate couplers
- **Reduce cost per MV by a factor 20: to make the LC feasible**
  - New cryomodule concept for cryolosses, cost and filling factor (for real estate gradient)
  - All subsystems designed for large scale production
  - **Reliability and quality control as a general guide line**

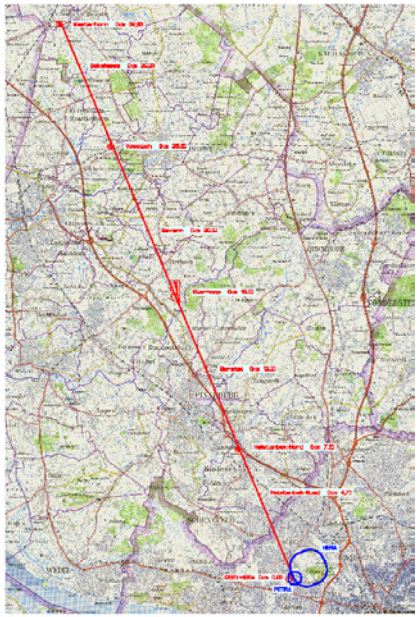
### Basic goals on Machine Design

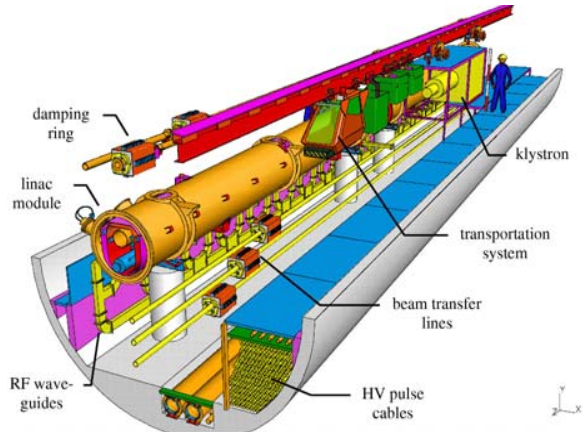
- **Design a Linear Collider based on the Cold Linac peculiarities**
- **Maximize Luminosity and optimize cost for a given plug power**
- **Design and quote major subsystems:** DR, Positron Source, BDS, etc.
- **Put all together in a consistent TDR, including cost estimation**

# The TESLA TDR – 500 GeV → 800 GeV



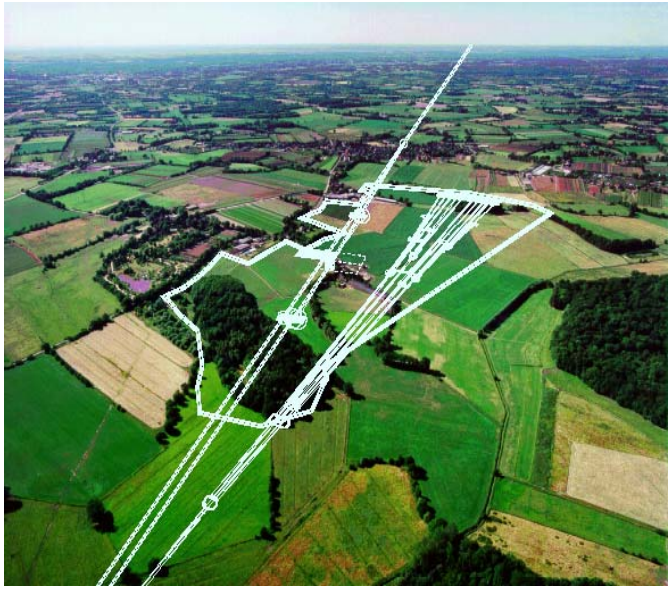



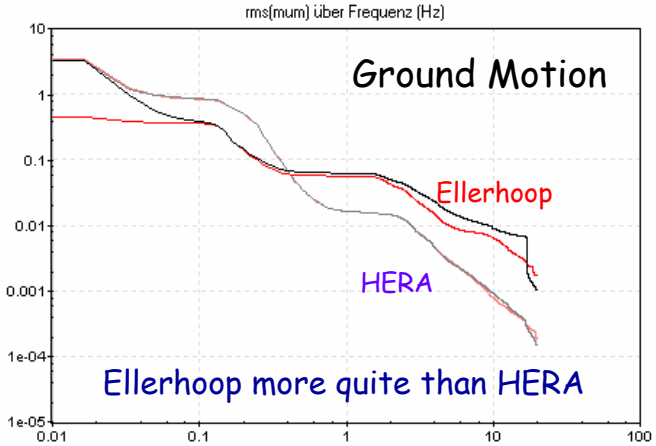


# About the TESLA TDR Site

TESLA in the Hamburg area

Interaction Points and X-FEL at Ellerhoop





# TESLA 500 GeV Parameters

From the TESLA TDR

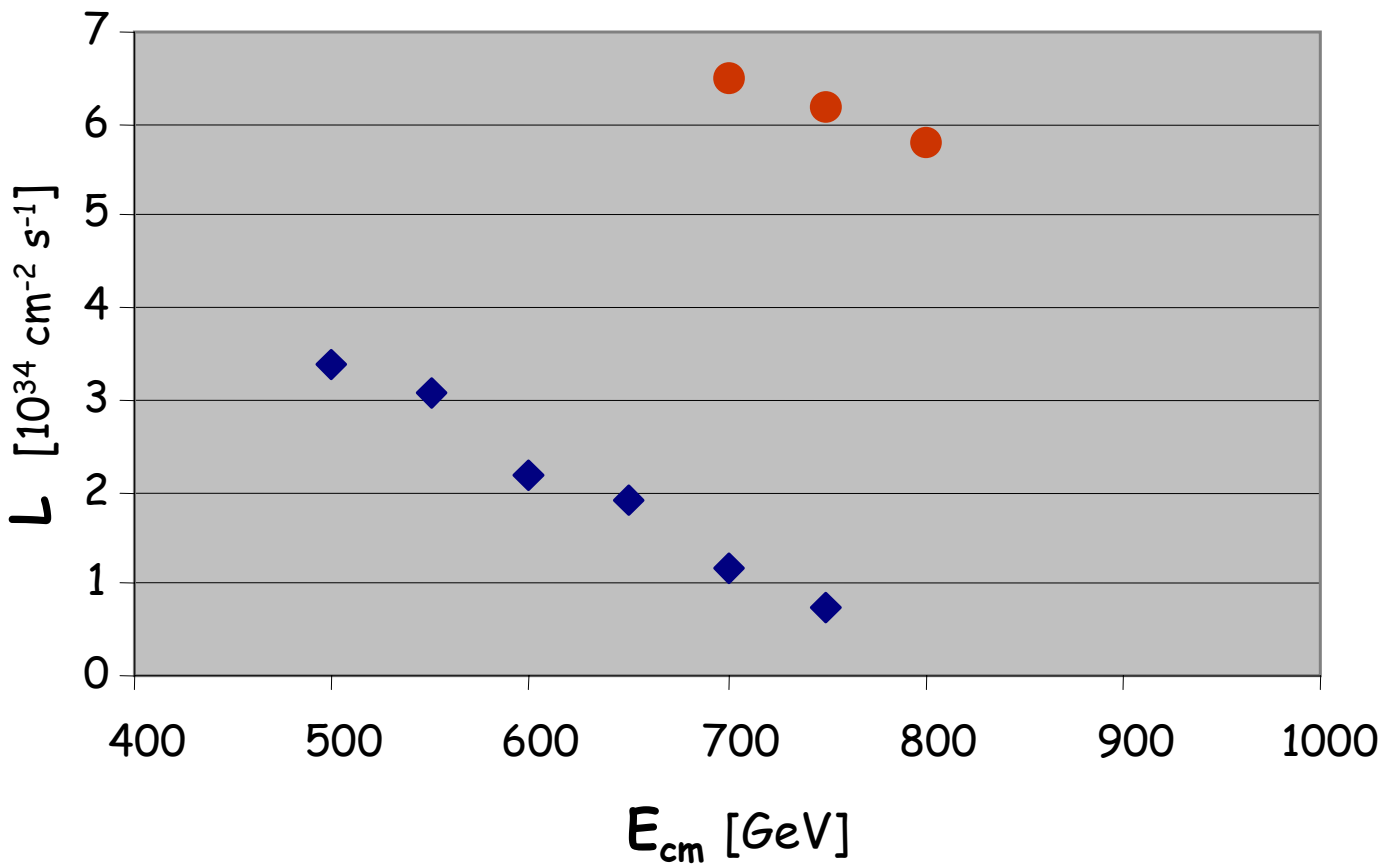
| | | |
|---|---|---|
| Accelerating gradient | $E_{acc}$ [MV/m] | 23.4 |
| RF-frequency | $f_{RF}$ [GHz] | 1.3 |
| Fill factor | | 0.747 |
| Total site length | $L_{tot}$ [km] | 33 |
| Active length | [km] | 21.8 |
| No. of accelerator structures | | 21024 |
| No. of klystrons | | 584 |
| Klystron peak power | [MW] | 9.5 |
| Repetition rate | $f_{rep}$ [Hz] | 5 |
| Beam pulse length | $T_P$ [$\mu$s] | 950 |
| RF-pulse length | $T_{RF}$ [$\mu$s] | 1370 |
| No. of bunches per pulse | $n_b$ | 2820 |
| Bunch spacing | $\Delta t_b$ [ns] | 337 |
| Charge per bunch | $N_e$ [$10^{10}$] | 2 |
| Emittance at IP | $\gamma\varepsilon_{x,y}$ [$10^{-6}$m] | 10, 0.03 |
| Beta at IP | $\beta^*_{x,y}$ [mm] | 15, 0.4 |
| Beam size at IP | $\sigma^*_{x,y}$ [nm] | 553, 5 |
| Bunch length at IP | $\sigma_z$ [mm] | 0.3 |
| Beamstrahlung | $\delta_E$ [%] | 3.2 |
| Luminosity | $L_{e+e-}$ [$10^{34}$cm$^{-2}$s$^{-1}$] | 3.4 |
| Power per beam | $P_b/2$ [MW] | 11.3 |
| Two-linac primary electric power (main linac RF and cryogenic systems) | $P_{AC}$ [MW] | 97 |

# TDR Luminosity vs. cm Energy

All cavities at 35 MV/m

**Baseline** ◆ no additional cost

**Upgrade** ● more RF & cryogenics



# Site power: 140 MW

500 GeV baseline

## Main Linacs
97MW

RF:
76MW

78%

65%

60%

Cryogenics:
21MW

## Sub-Systems
43MW

Injectors

Damping rings

BDS

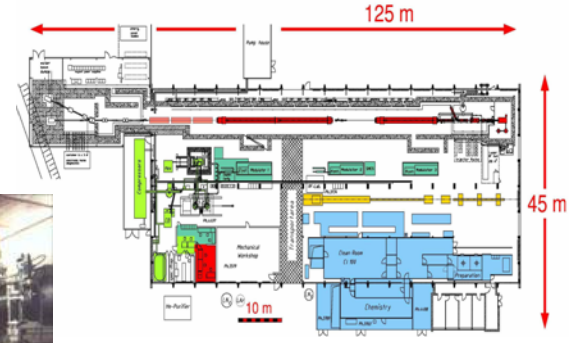
Auxiliaries

**Beam**
22.6MW

# TESLA Collaboration Milestones

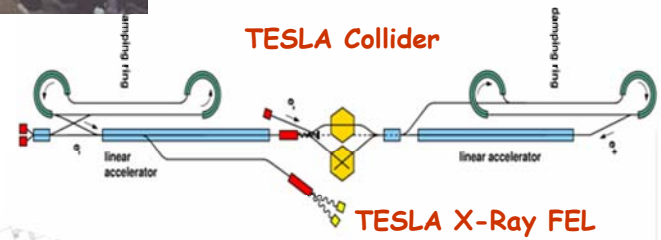
- February 1992 – 1° TESLA Collaboration Board Meeting @ DESY
- March 1993 - "A Proposal to Construct and Test Prototype Superconducting RF Structures for Linear Colliders"
- **1995 – 25 MV/m in multi-cell cavity**
- May 1996 – First beam at TTF
- March 2001 – First SASE-FEL Saturation at TTF
- March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

Infrastructure @ DESY in Hall 3

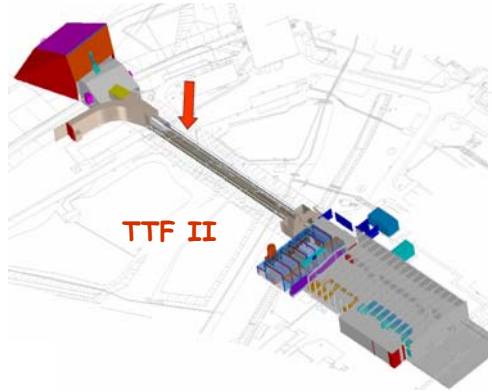



TTF I

TESLA Collider




TESLA X-Ray FEL



TTF II

# Electro-Polishing & Baking for 35 MV/m

The AC 70 example

## EP at the DESY plant

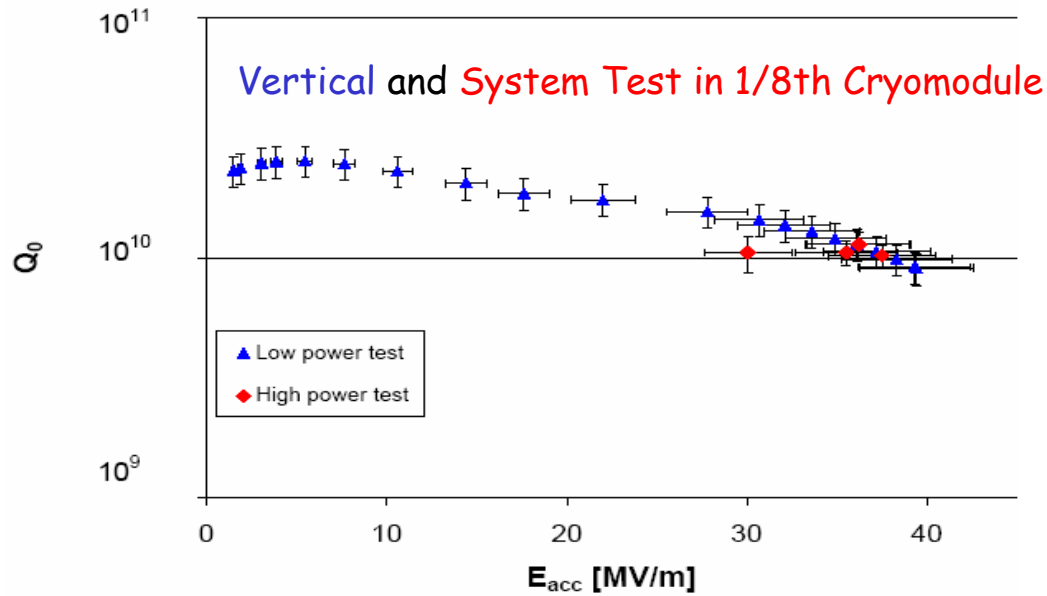
- **Low Field Emission**

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)**

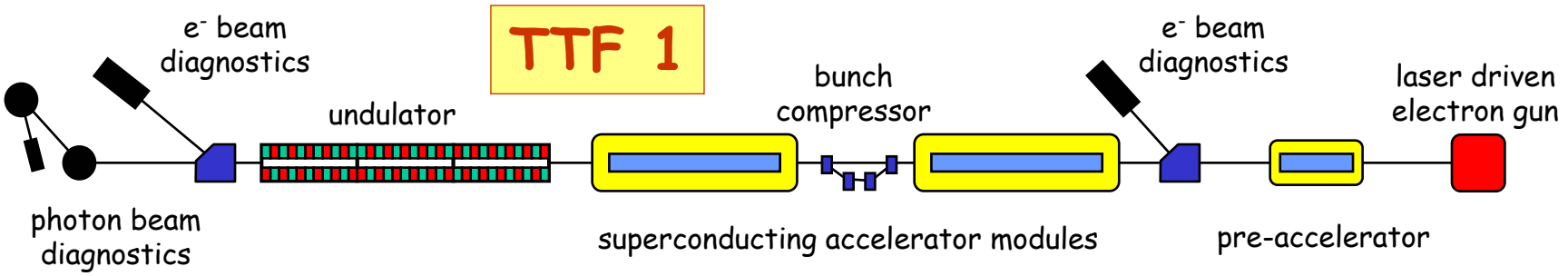
- less local field enhancement
- High Pressure Rinsing more effective
- **Field Emission onset at higher field**

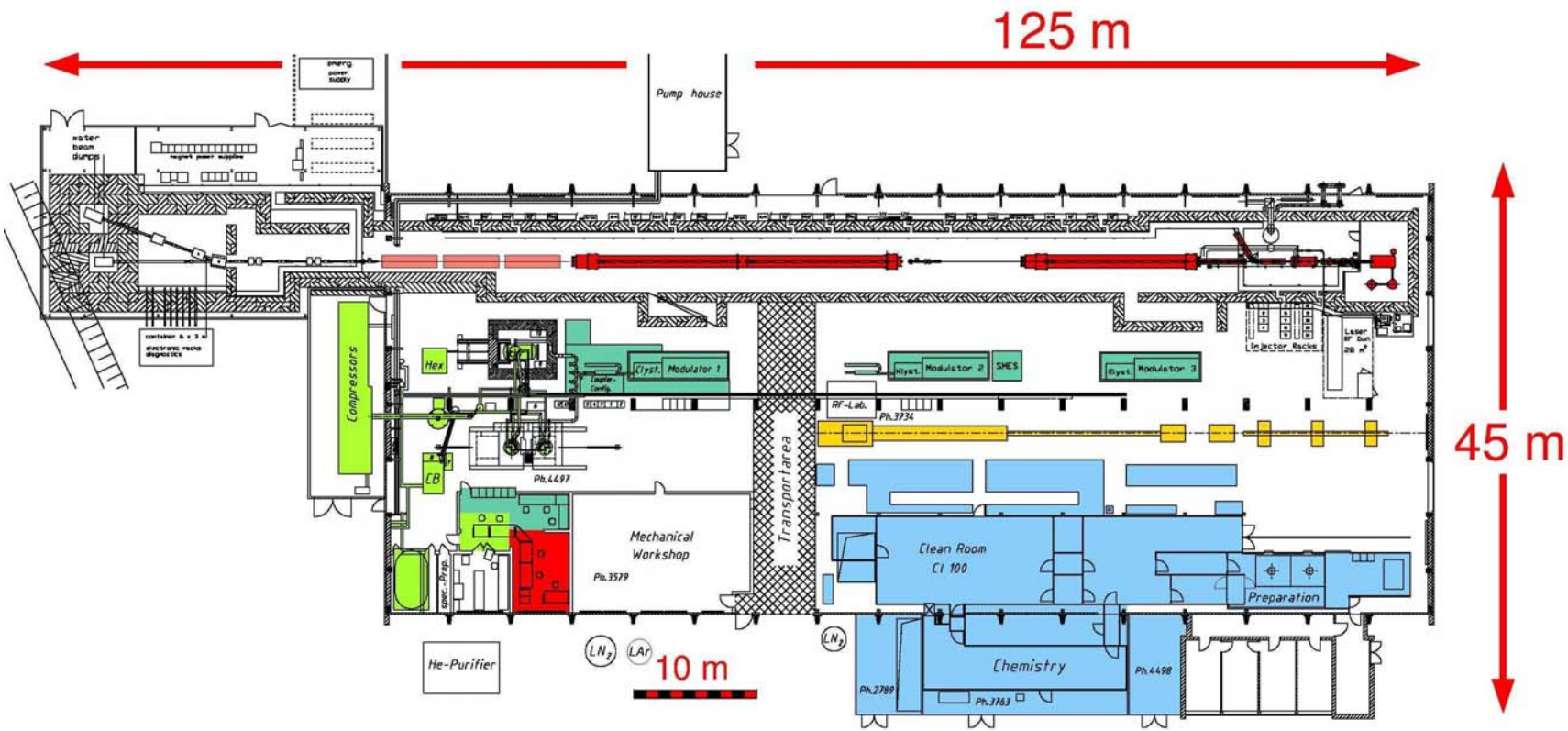
## In-Situ Baking

@ 120-140 ° C for 24-48 hours

- to re-distribute oxygen at the surface
- **cures Q drop at high field**

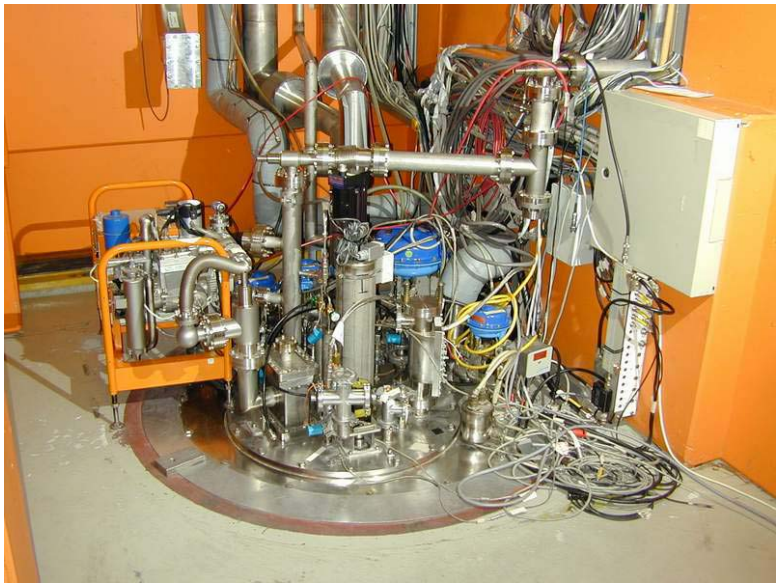
# A dedicated new infrastructure at DESY



# 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"

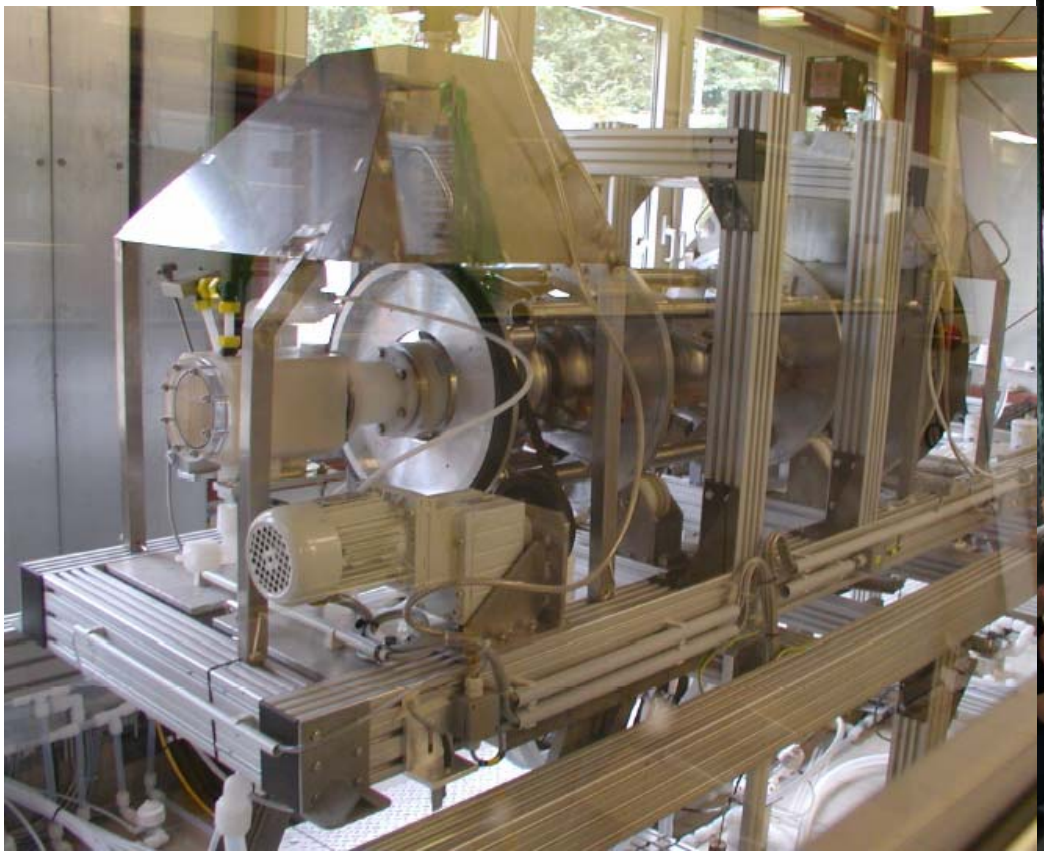
Chechia is a horizontal cryostat to test fully equipped cavities

- 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

# EP at DESY fully commissioned

**DESY EP Infrastructure fully operational**

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



# String Assembly

The assembly of a string of 8 cavities

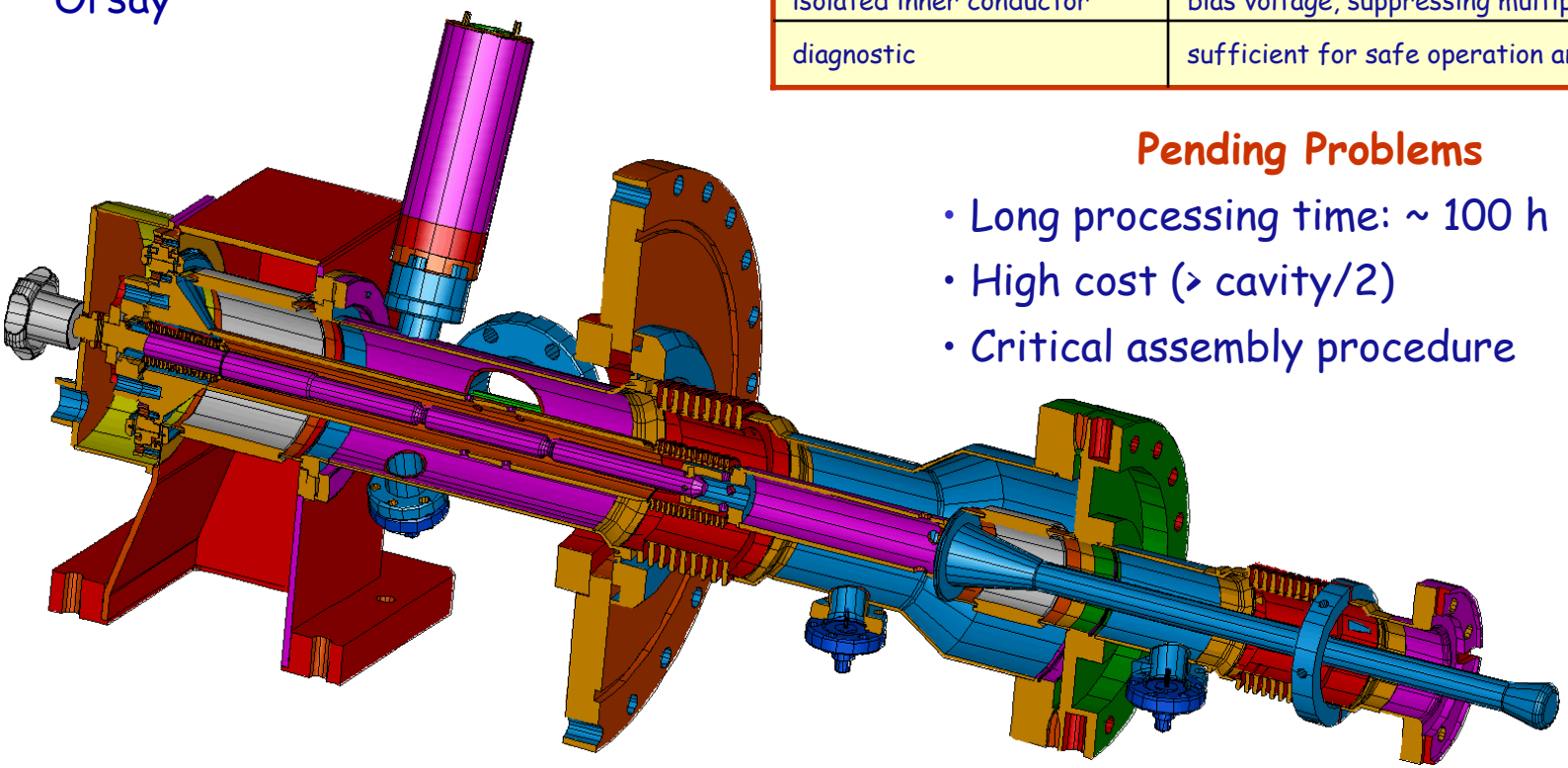
- is a standard procedure
- is done by technicians from the TESLA Collaboration
- is well documented using the cavity database as well as an Engineering Data Management System
- was the basis for two industrial studies.
- ready to transfer to industry.

The inter-cavity connection is done in class 10 cleanrooms

# Ancillaries: Power Coupler

- 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,<br>800 μsec flat top with beam |
| two windows, TiN coated | • safe operation<br>• 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 |

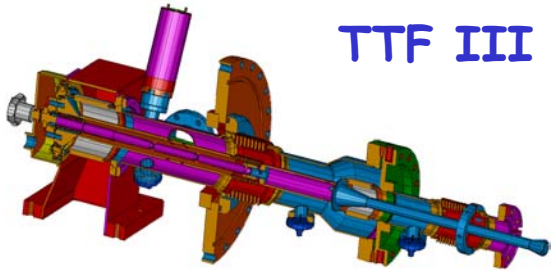


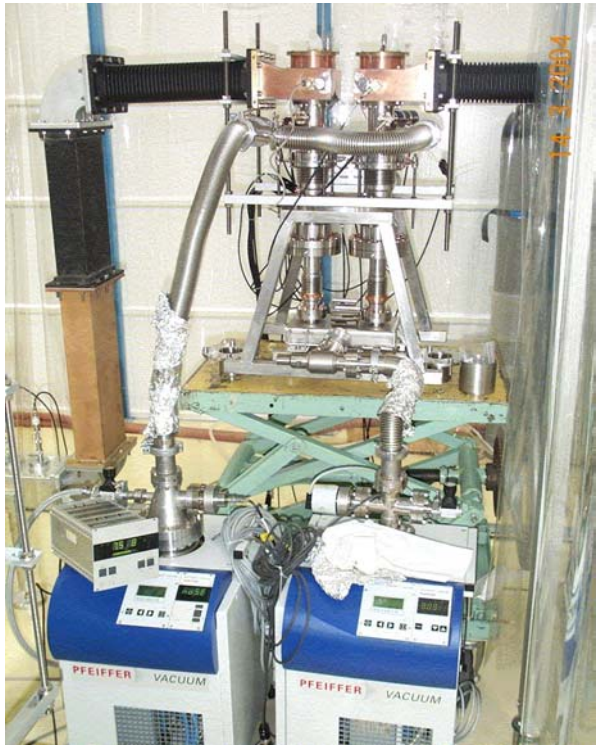
**Pending Problems**

- Long processing time: ~ 100 h
- High cost (> cavity/2)
- Critical assembly procedure

# Coupler Development at LAL-Orsay

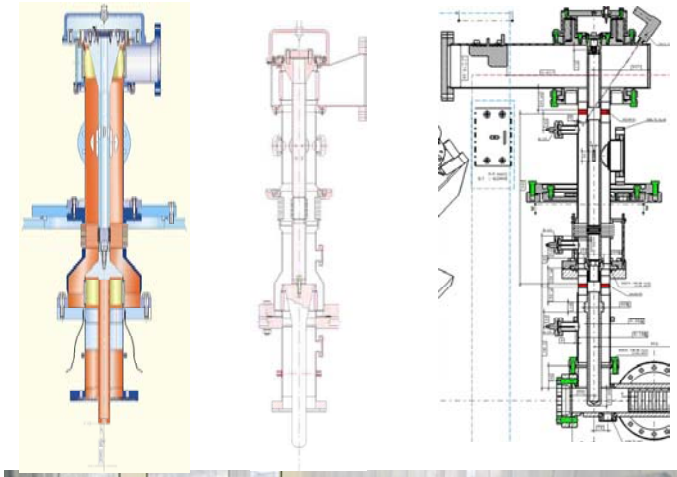
TTF III






High Power Coupler Test Stand

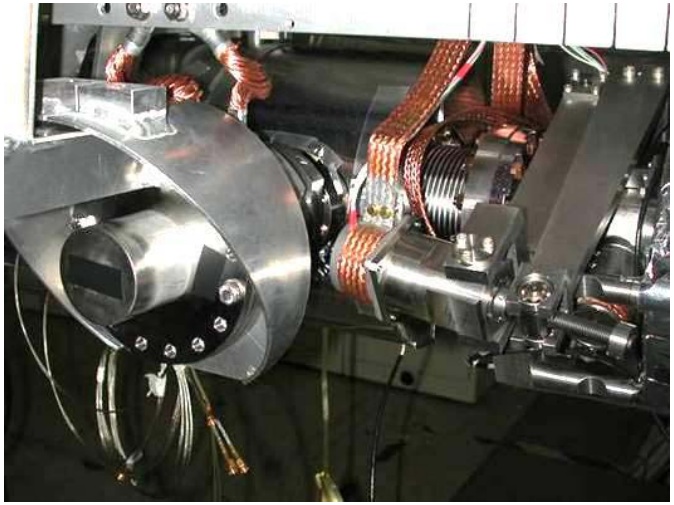
Alternative Designs

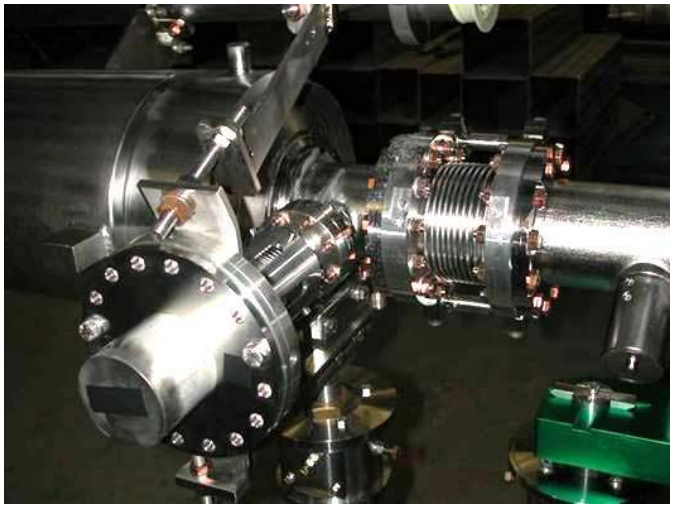


Clean room assembly

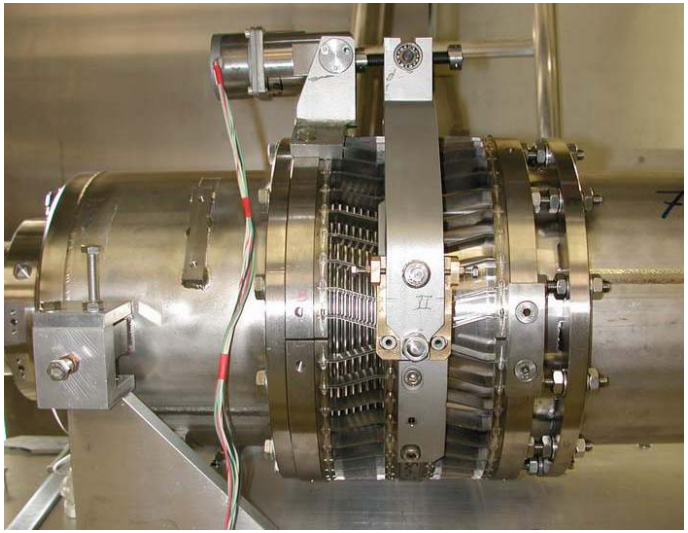
# Ancillaries: Cavity Tuners

## The Saclay Tuner in TTF

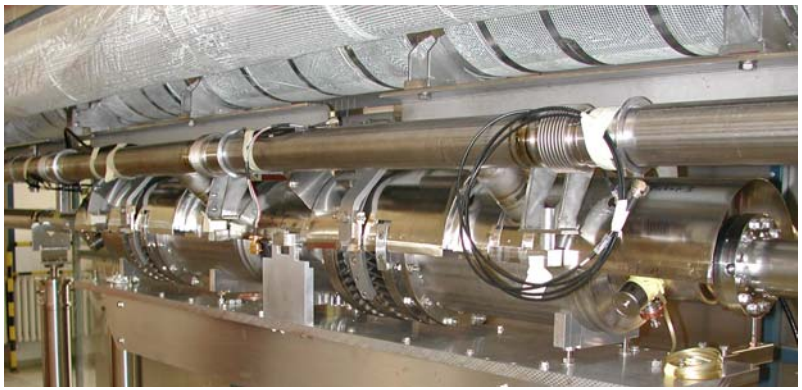




## The INFN Blade-Tuner



Successfully operated with superstructures

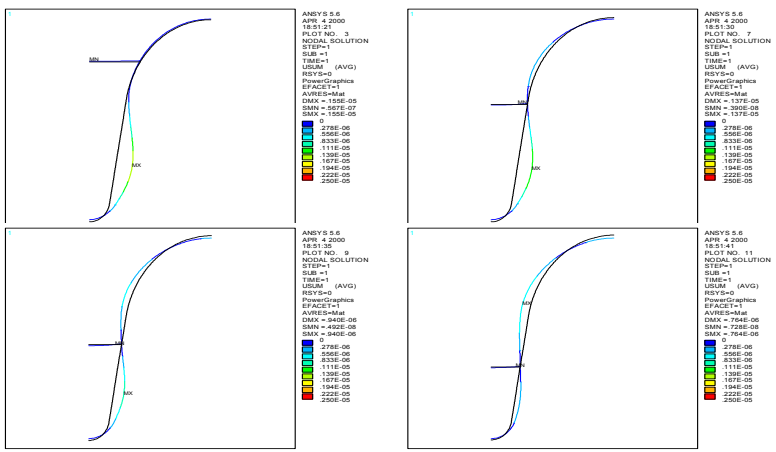


# Lorentz Force Detuning

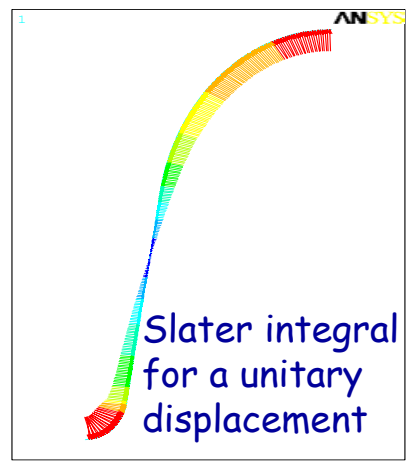
- High magnetic field and high currents on the cavity surface produce a Lorentz force

$$\vec{F}_{em} = \vec{F}_{Lorentz} = \frac{d\vec{p}}{dt} = q\ (\vec{E} + \vec{v} \times \vec{B}) = \vec{F}_{el} + \vec{F}_{mag}$$

- At each RF millisecond power pulse the Lorentz force produces a cavity deformation at the micrometer level



Cavity deformation for different stiffening ring radial position

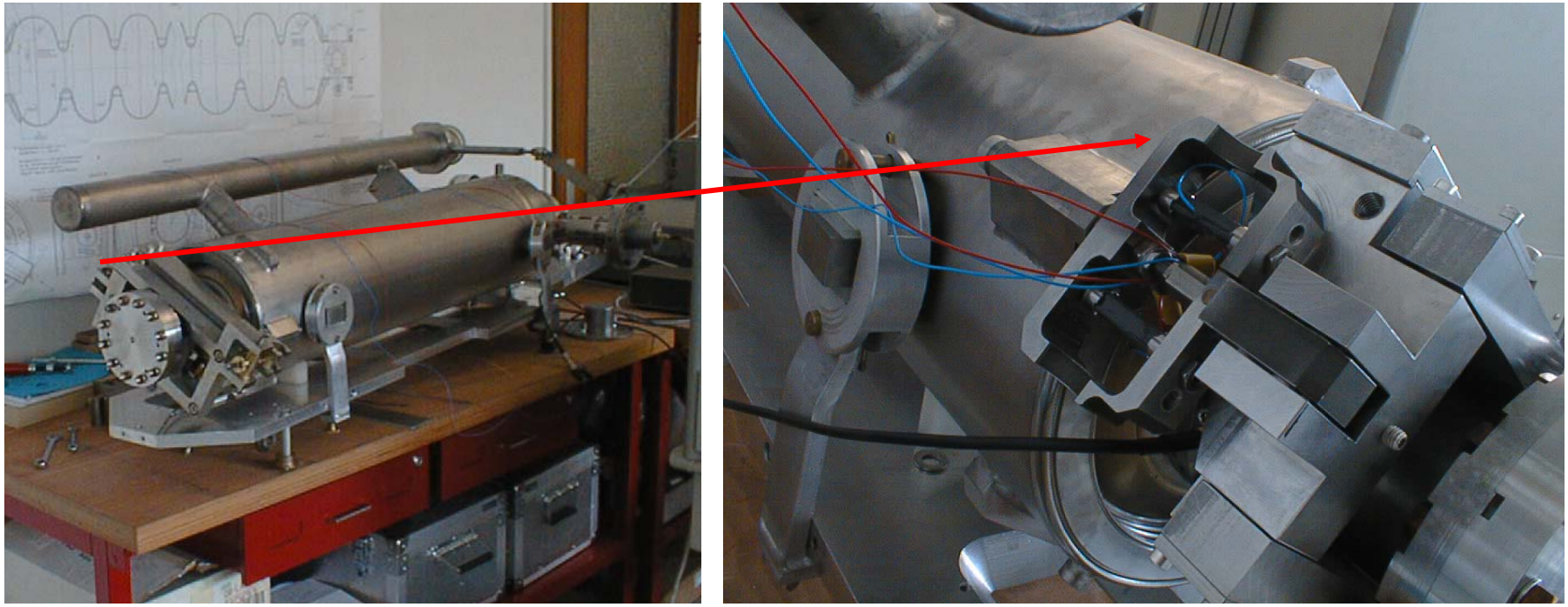



Slater integral for a unitary displacement

- Due to the high Q and the consequent small frequency band, ~ 400 Hz over 1.3 GHz, the cavity moves from the original tuning
- At 35 MV/m the Lorentz force detuning is ~ 1000 Hz

# Piezo-assisted Tuner on AC73

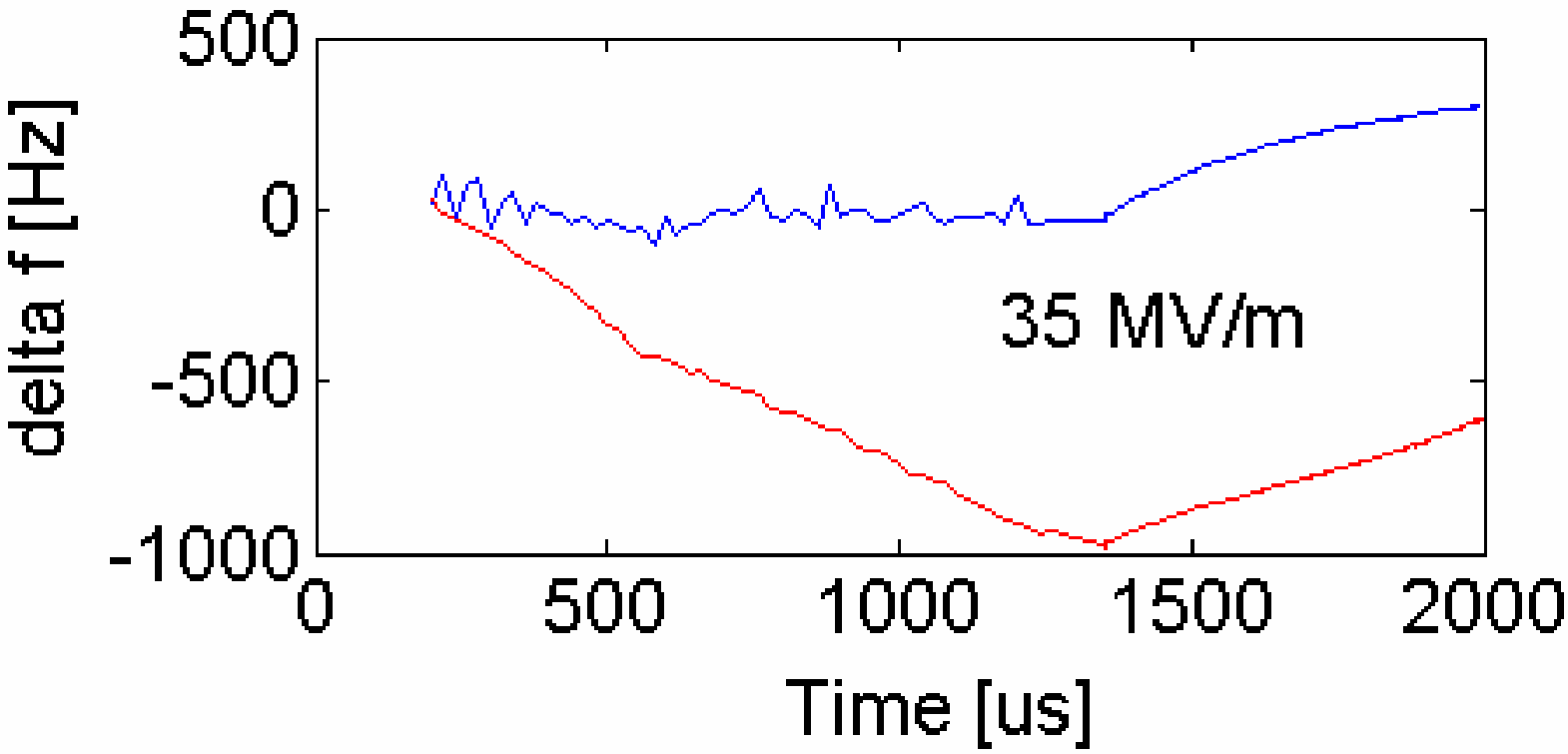
- To compensate for Lorentz force detuning during the 1 ms RF pulse
  Feed-Forward
- To counteract mechanical noise, "microphonics"
  Feed-Back



# Successful Compensation @ 35 MV/m

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

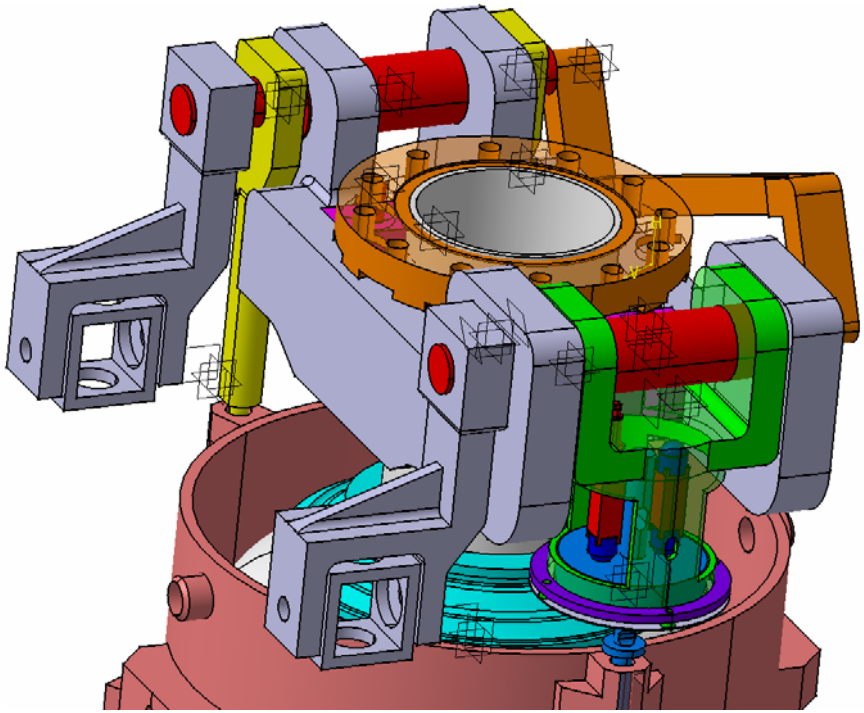
- Piezo-compensation on: just feed-forward resonant compensation
- Piezo-compensation off



# New Saclay Tuner for XFEL

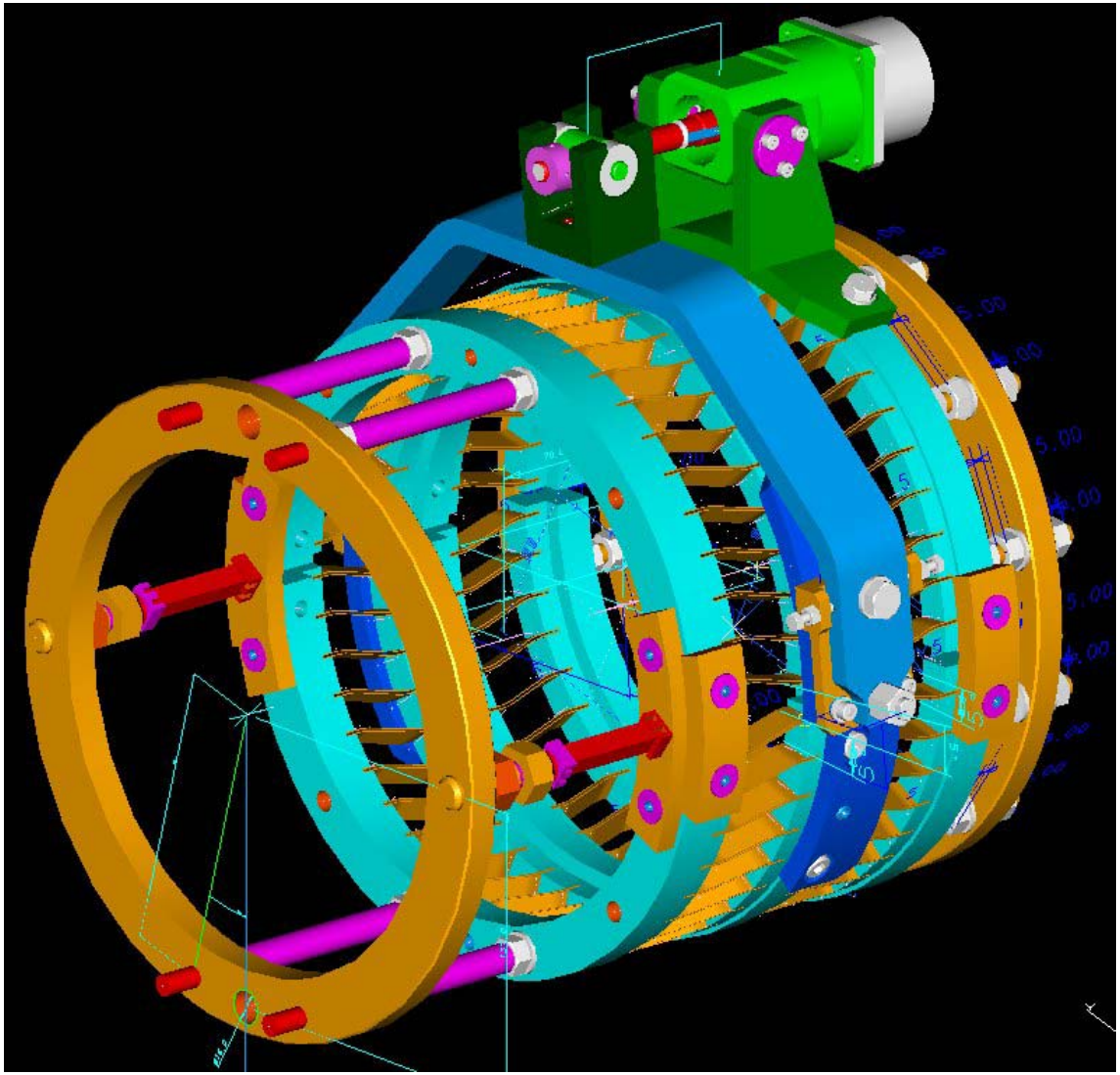
***New design with piezos***

- **CARE/JRA-SRF**
- **SOLEIL upgrades**
- **larger rigidity**

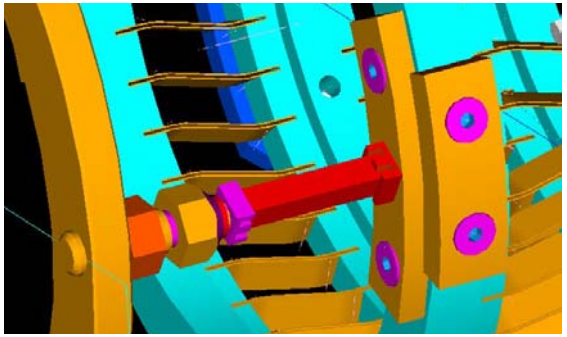


- Fabrication of 2 tuners since beginning of 2005
- 12 NOLIAC piezos, 2 PHYTRON stepping motors ordered
- Coll. with IPN Orsay: CEA send NOLIAC piezos to IPN for characterization, and IPN send P.I. piezos for tests on tuners
- Coll. with INFN-Milano for measurement with stress sensors @ 2K

# New INFN Blade-Tuner for ILC



- Integration of piezos for Lorentz forces and microphonics completed.
- Final Drawing delivered for fabrication.
- Two prototype, including the modified helium tank, are expected by October 2005
- Cold tests results by fall 2005 (DESY, BESSY, Cornell?)





Status as on February 1st, 2005

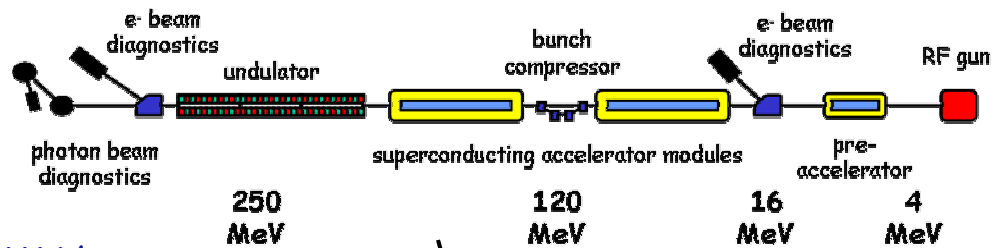
# TTF and Cryomodules

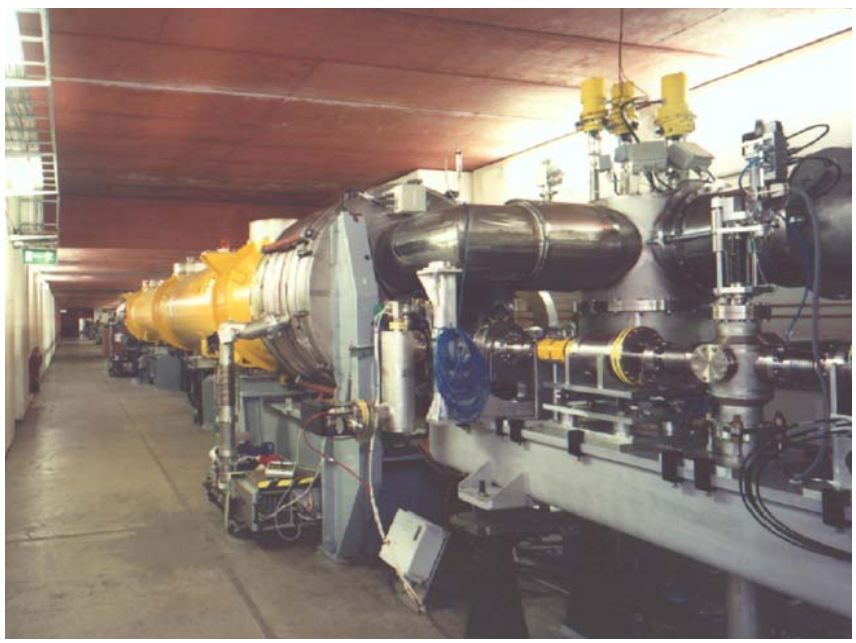
## TTF = TESLA Test Facility

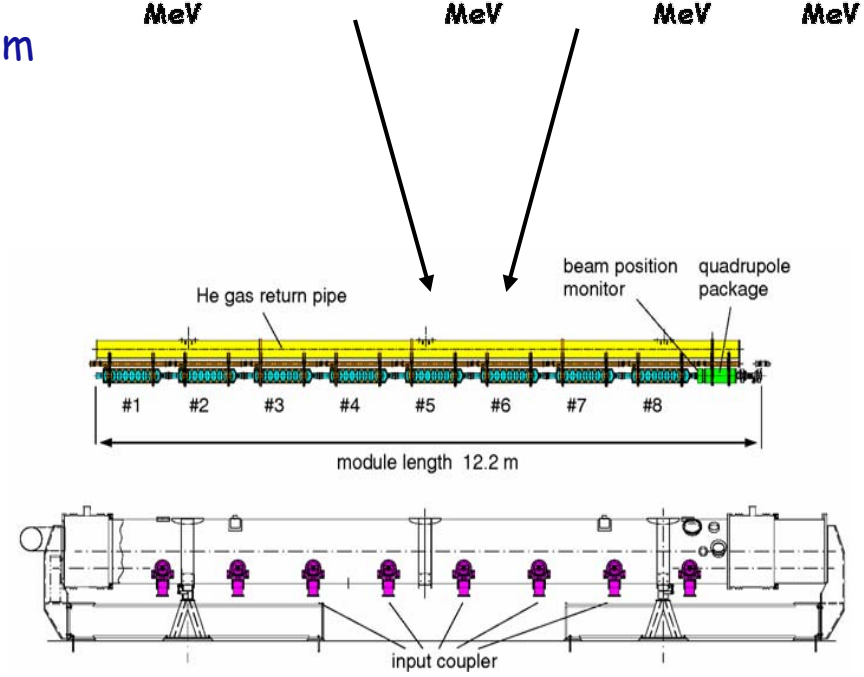
### TTF Goals:

- Demonstrate that Superconducting RF technology is suitable for LC
- Operate TTF at $E_{acc}$ > 15 MV/m
- Develop cavity technology for Eacc > 25 MV/m

TTF as operated for SASE FEL





# TESLA Cryomodule Design Rationales

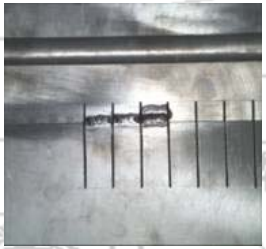
- High Performance Cryomodule was central for the TESLA Mission
  - More then one order of magnitude was to be gained in term of capital and operational cost
- High filling factor: to maximize real estate gradient
  - Long sub-units with many cavities (and quad): cryomodules
  - Sub-units connected in longer strings
  - Cooling and return pipes integrated into a unique cryomodule
- Low cost per meter: to be compatible with a long TeV Collider
  - Cryomodule used also for feeding and return pipes
  - Minimize the number of cold to warm connections for static losses
  - Minimize the use of special components and materials
  - Modular design using the simplest possible solution
- Easy to be alligned and stable: to fullfil beam requirements

# Performing Cryomodules

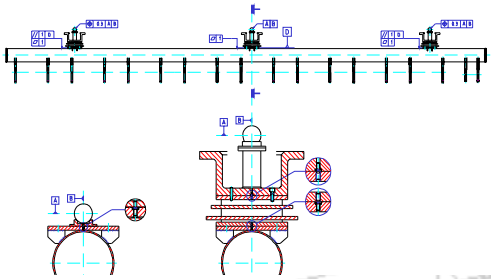
## Three cryomodule generations to:

- improve simplicity and performances
- minimize costs

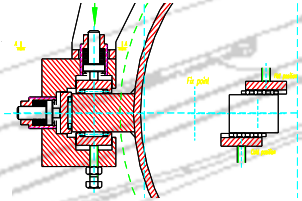
"Finger Welded" Shields



Reliable Alignment Strategy

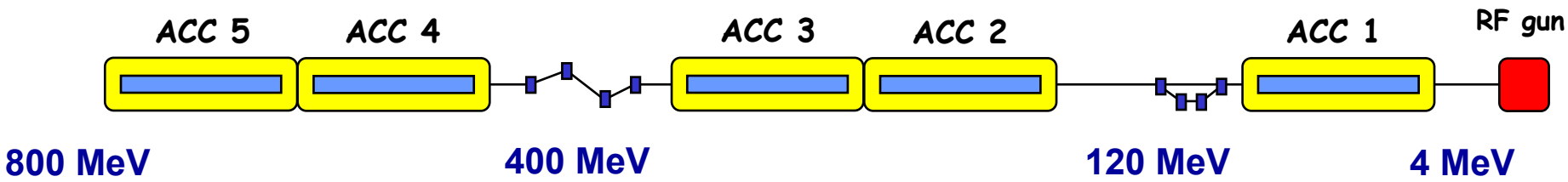


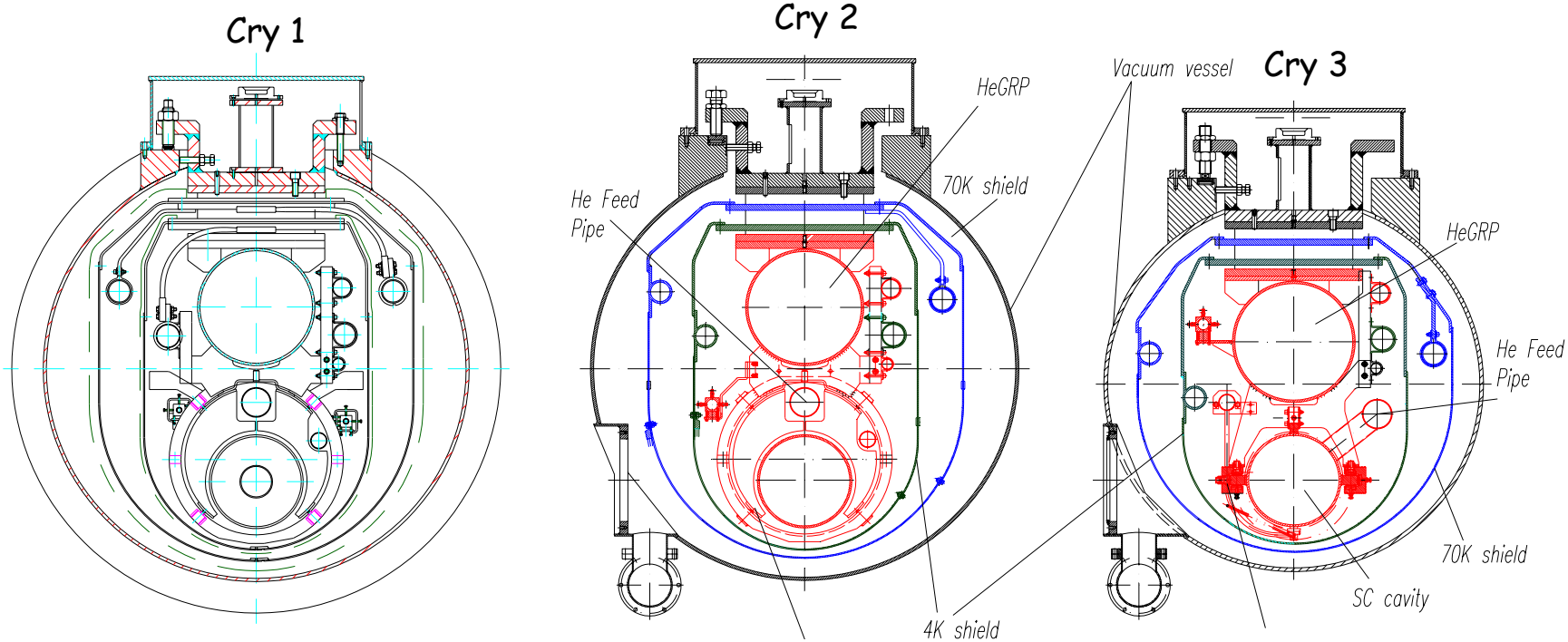
Sliding Fixtures @ 2 K



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

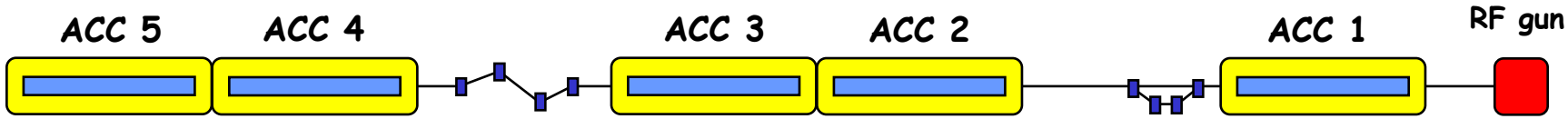
# Three Generation Cryomodules in TTF




Module 1 Module 2 & 3 Module 4 & 5

# Cryoodules installed in TTF II



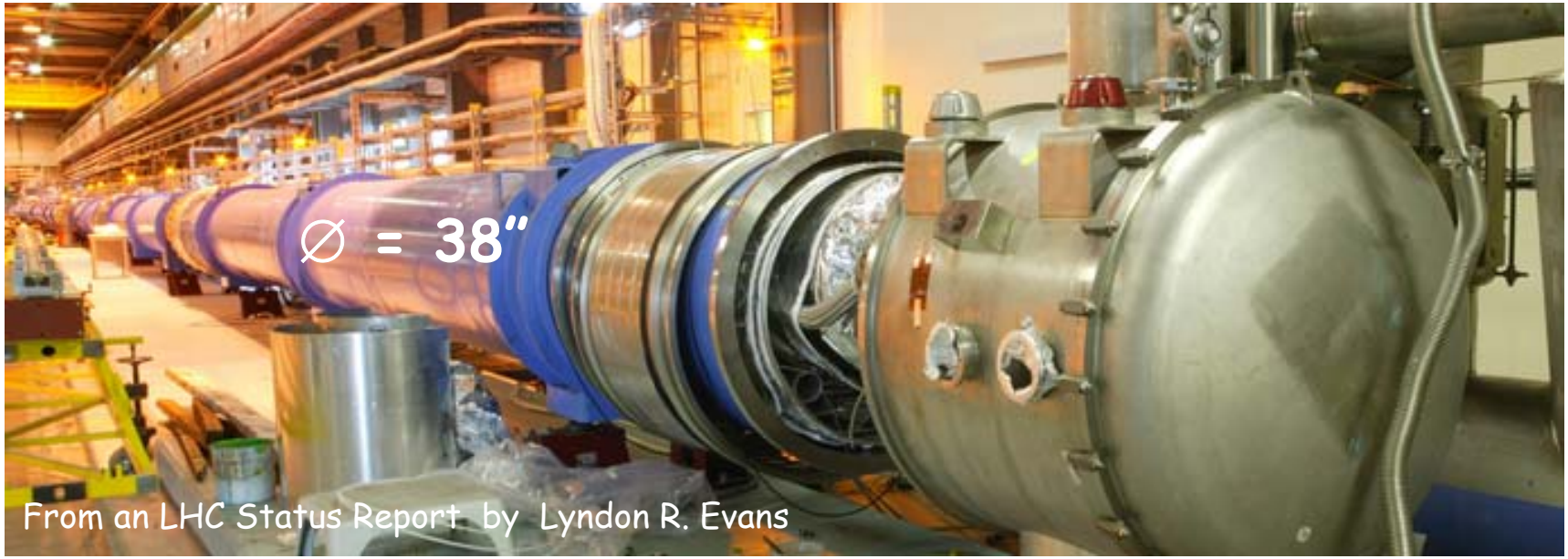

800 MeV 400 MeV 120 MeV 4 MeV

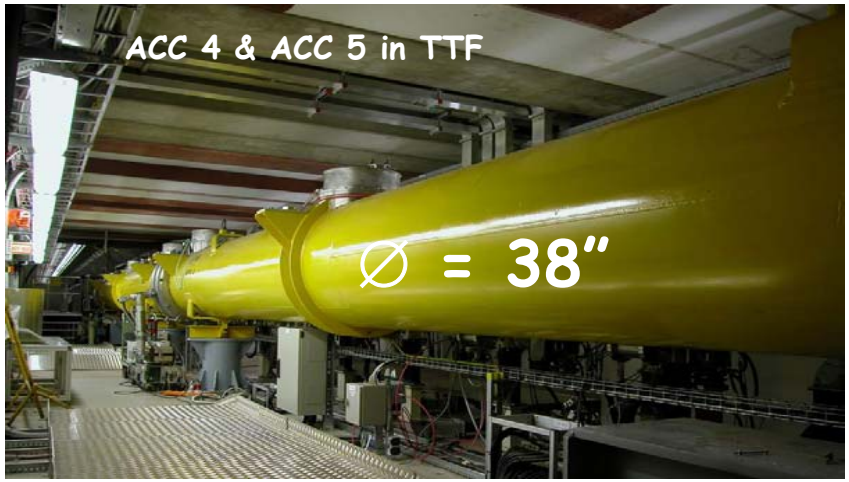
# TTF Cryomodule Operation Experience

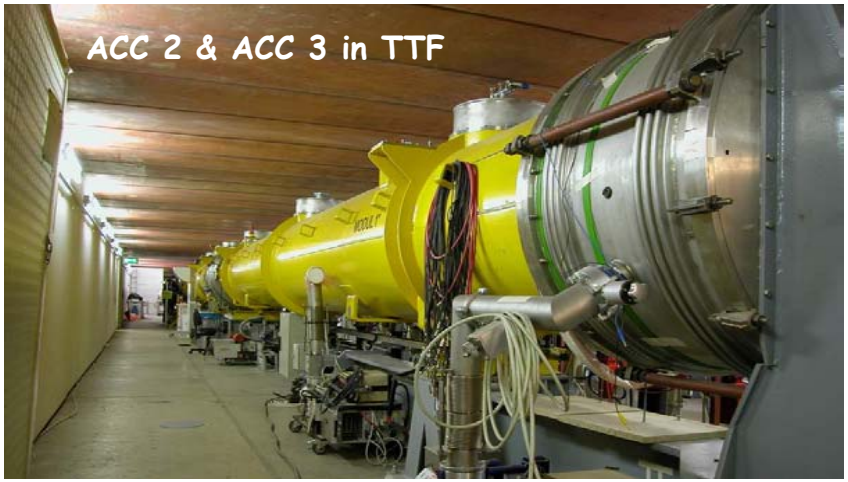
| | Type | Installation date | Cold time [months] |
|---|---|---|---|
| CryoCap | | Oct 96 | 50 |
| M1 | 1 | Mar 97 | 5 |
| M1 rep. | 2 | Jan 98 | 12 |
| M2 | 2 | Sep 98 | 44 |
| M3 | 2 | Jun 99 | 35 |
| M1*<br>MSS | 2<br>2 | Jun 02 | 29<br>8 |
| M3*<br>M4<br>M5 | 2<br>3<br>3 | Apr 03 | 18<br>18<br>18 |
| M2* | 2 | Feb 04 | 15 |

10 July 2005

# LCH and TESLA Module Comparison

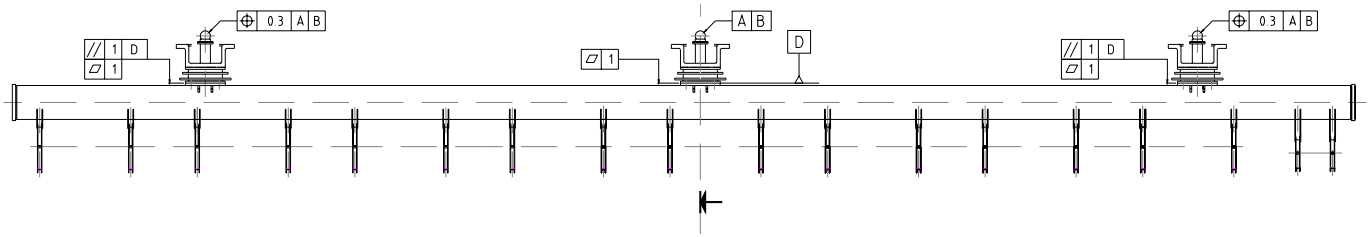


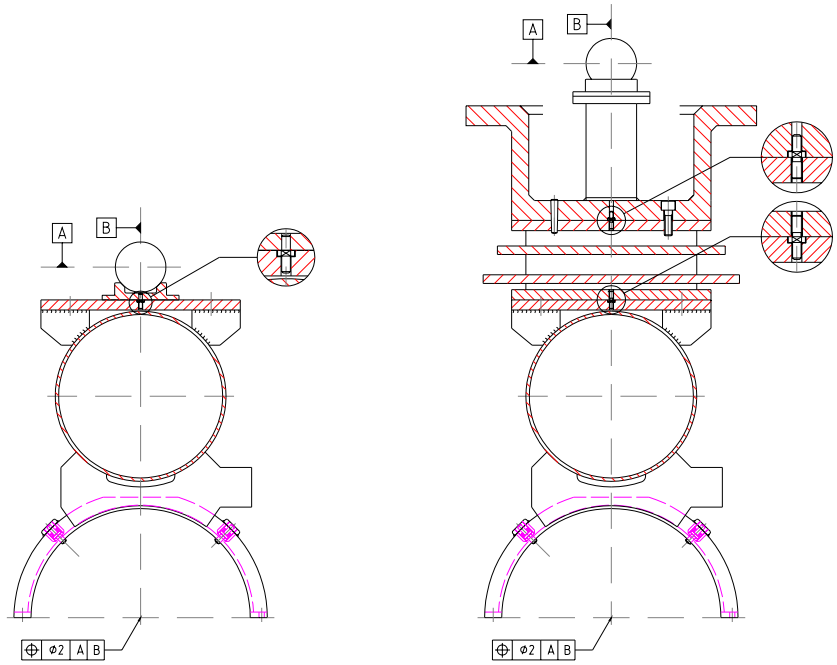



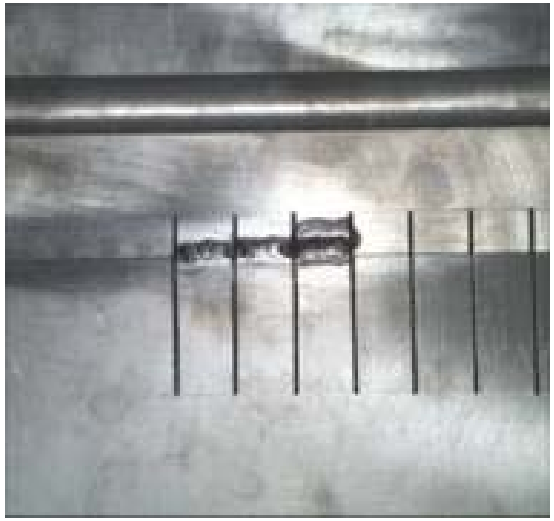
# 2nd Generation TESLA Cryomodule

- New fabrication sequence
- New strategy for tolerances





"Finger Welded" Shields



# 3rd Generation TESLA Cryomodule

- **Reduce the Cross Section and use a standard "pipeline" tube**
  - Redistribute the internal components
  - Reduce the distances to the minimum

- **Improve the connection of the active elements to the HeGRP**
  - Active component longitudinal position determined by an invar rod
  - Sliding fixtures to allow "Semi Rigid Coupler" and Superstructures

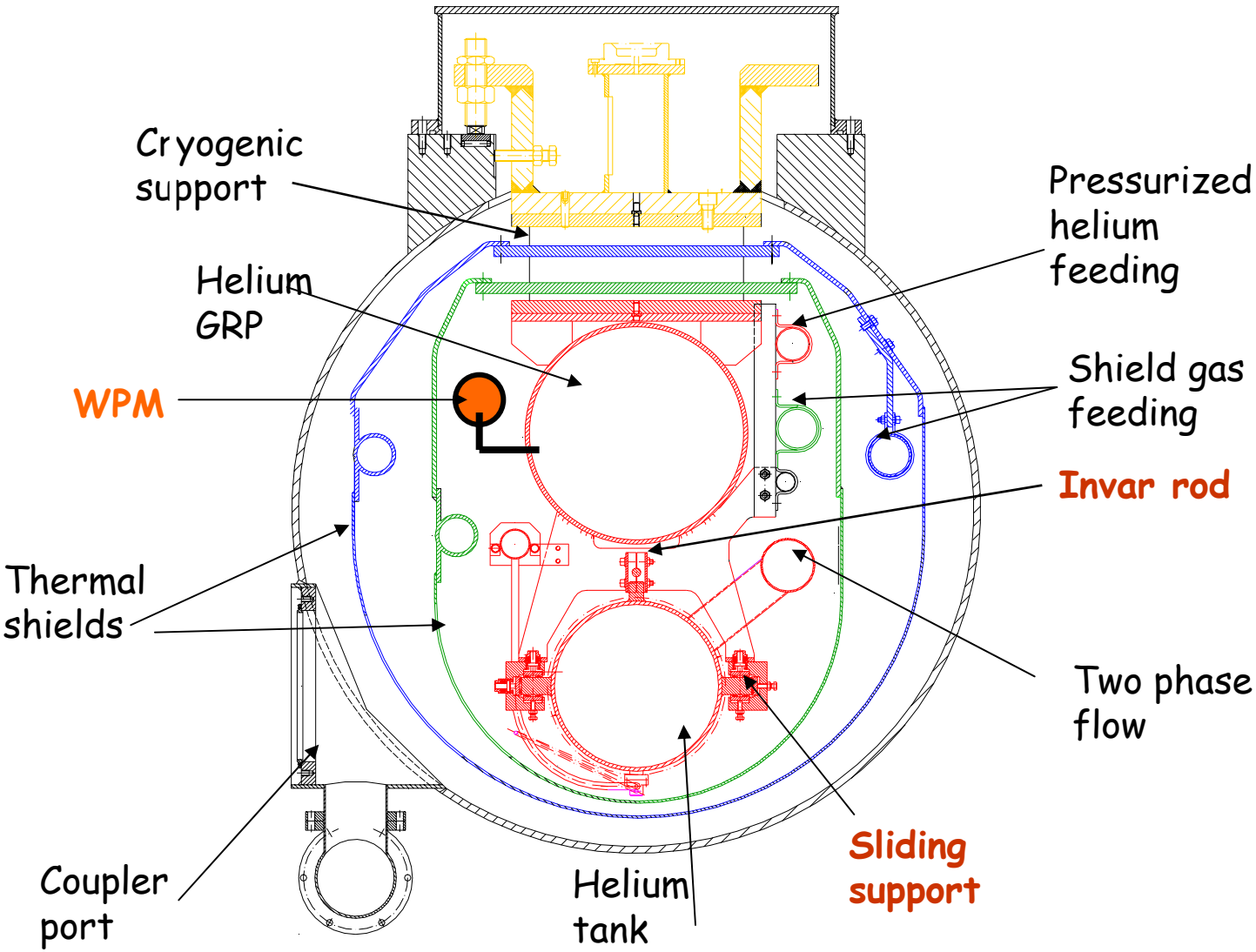
**Reduce alignment sensitivity to the forces on the HeGRP edges**

  - Move the external posts closer to the edges

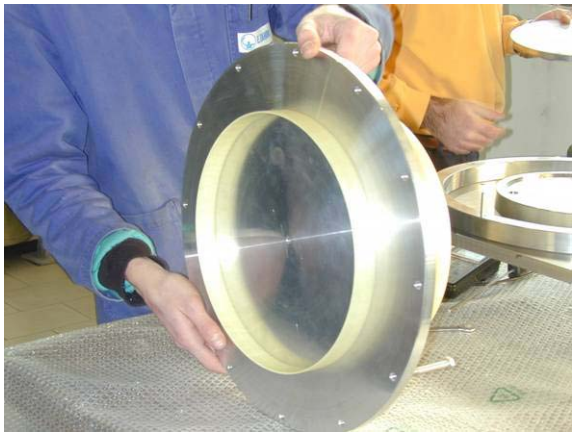
- **Further simplify the assembling procedure**
  - Simplify coupler cones and braids
  - Reduce by a factor two the shield components

- **System thought for mass production cost cutting**
  - Tolerances reduced to the required ones
  - Simpler components and standard tubes wherever possible

# Cry3 Cross Section

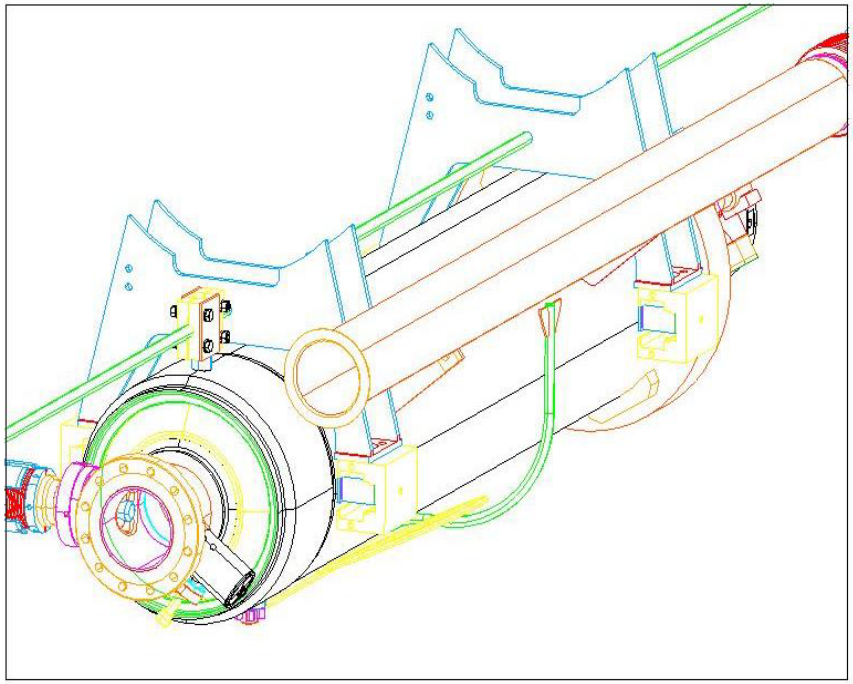


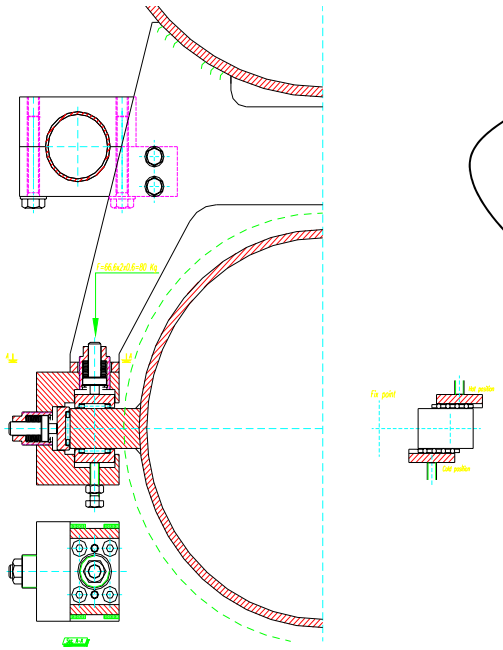
# Support Posts



# Sliding Fixtures to HeGRP

- Four C-Shaped SS elements clamp a titanium pad welded to the helium tank.
- Rolling needles reduce drastically the longitudinal friction
- Cavities result independent from the elongation and contraction of the HeGRP.
- Lateral and vertical position are defined by reference screws
- Longitudinal position by an Invar Rod

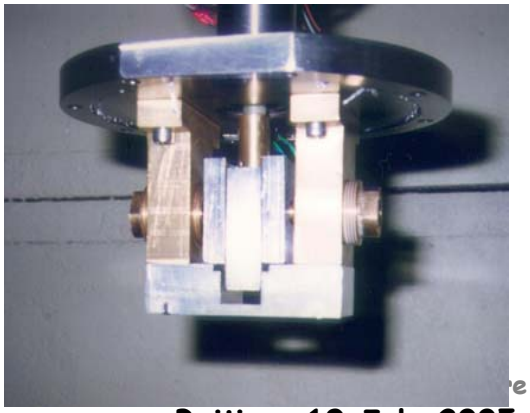




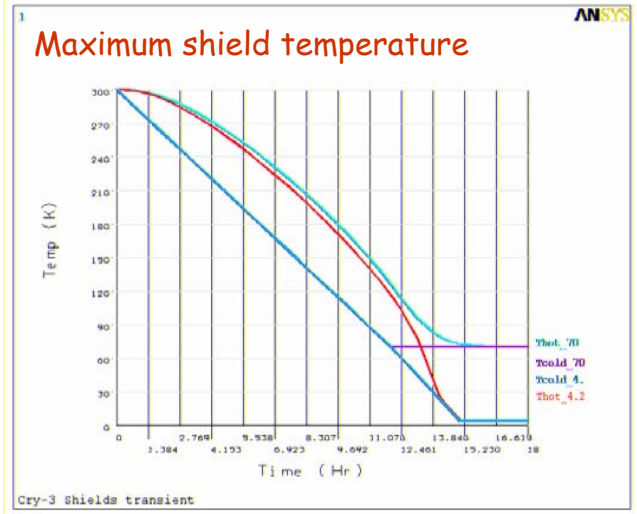
A Moke-up has been built to measure Friction force.

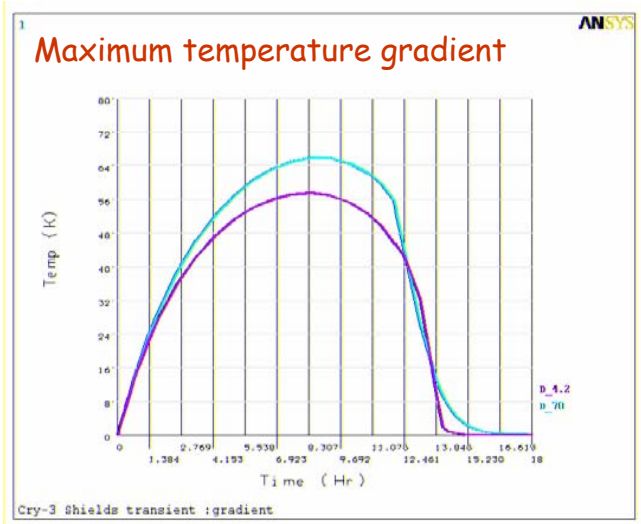
Results presented at CEC-99.

Friction force: 0.1 kgf

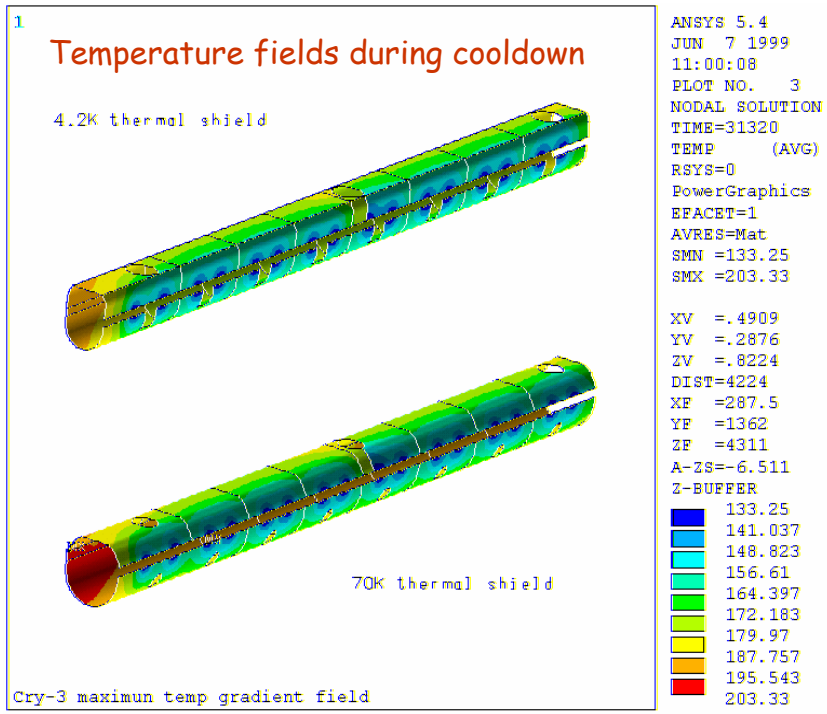


# Finger-Welded Shield Behavior




- Cooldown simulation of the 4.2 K and 70 K aluminum thermal shields.
- We used a simultaneous 12 hour linear cooldown.
- The maximal thermal gradient on the shields (upper left graph) is below 60 K, a safe value.
- The temperature fields show that the gradient is concentrated in the welding region, where the fingers unload the structure

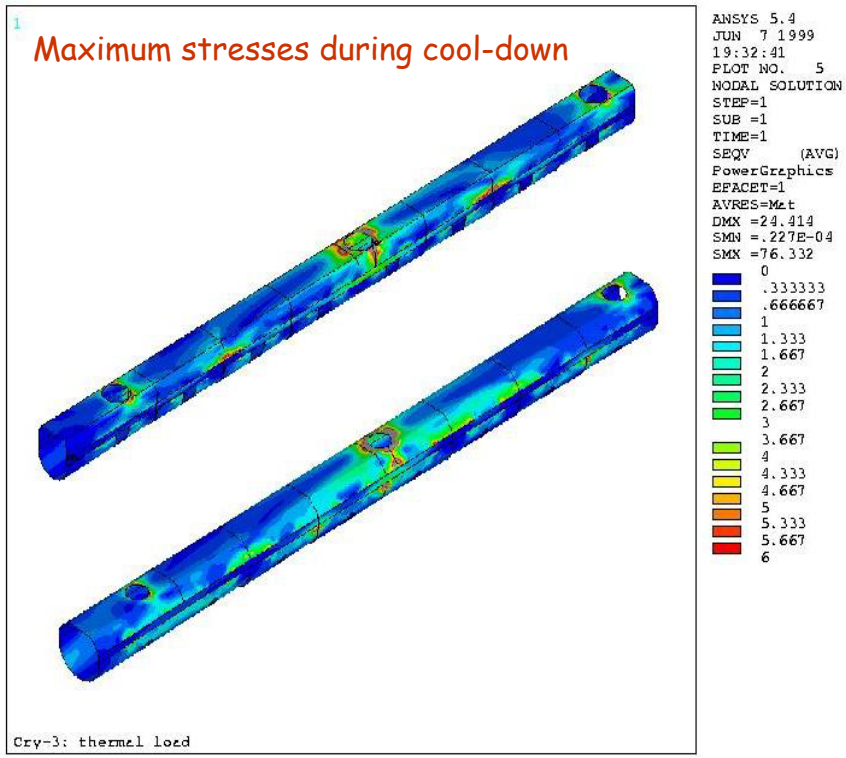


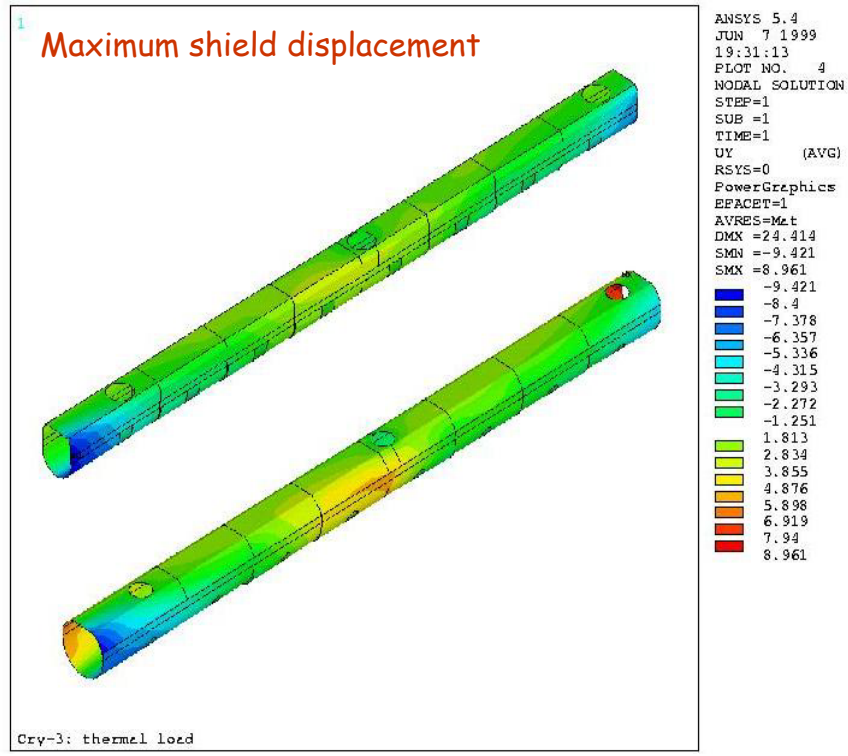
# Thermo-mechanical analysis of Shields

Applying the computed temperature field, deformations and stress distribution can be easily computed.

Maximum stresses are within acceptable limits

Maximum deformations due to asymmetric cooling is below 10 mm.



# WPMs to qualify alignment strategy

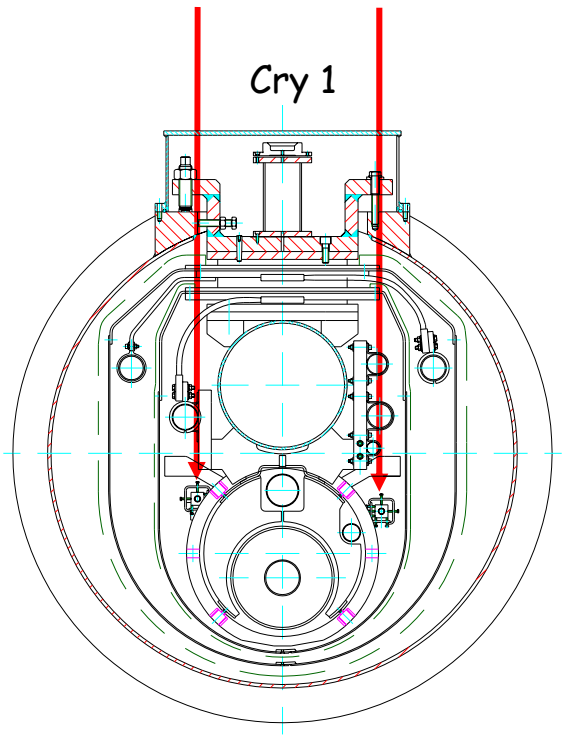
**WPM = Wire Position Monitor**

## On line monitoring of cold mass movements during cool-down, warm-up and operation

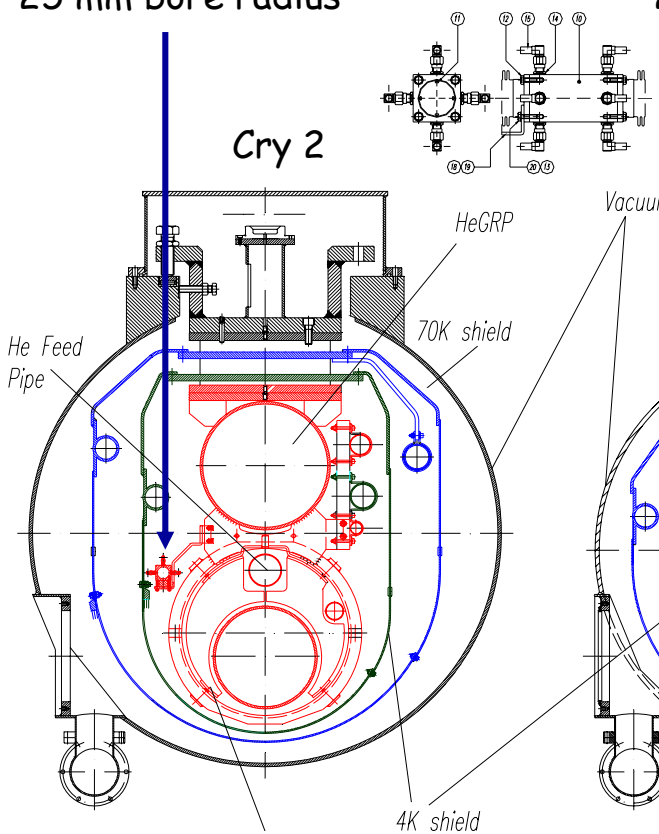
2 WPM lines with 2 x 18 sensors
4 sensors per active element
8 mm bore radius

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

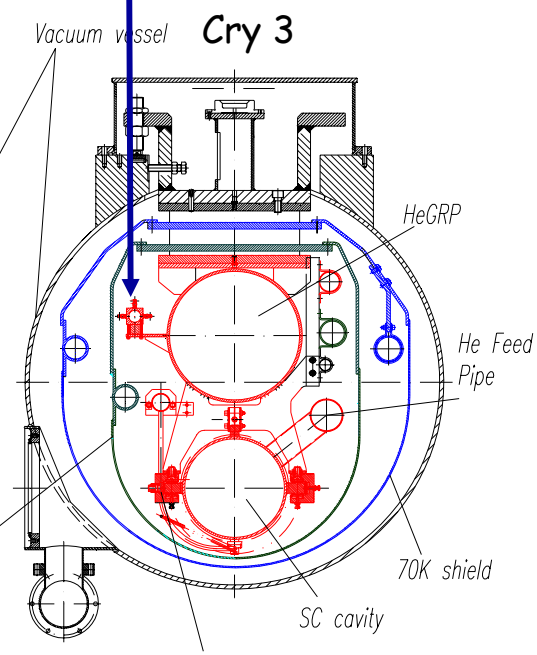
1 WPM line
7 sensors/module
25 mm bore radius




Module 1

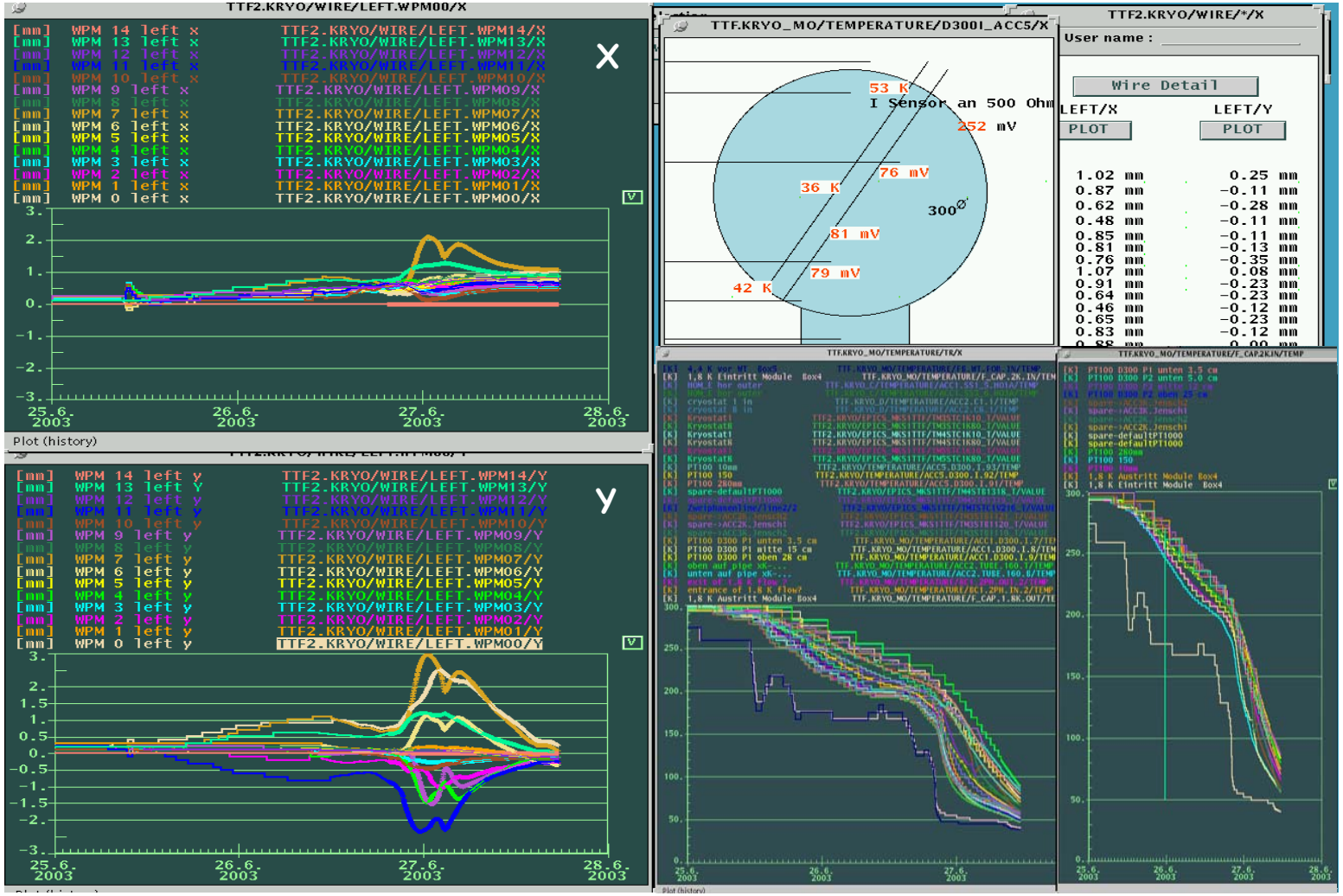



Module 2 & 3

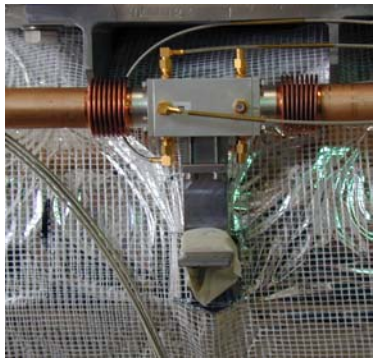


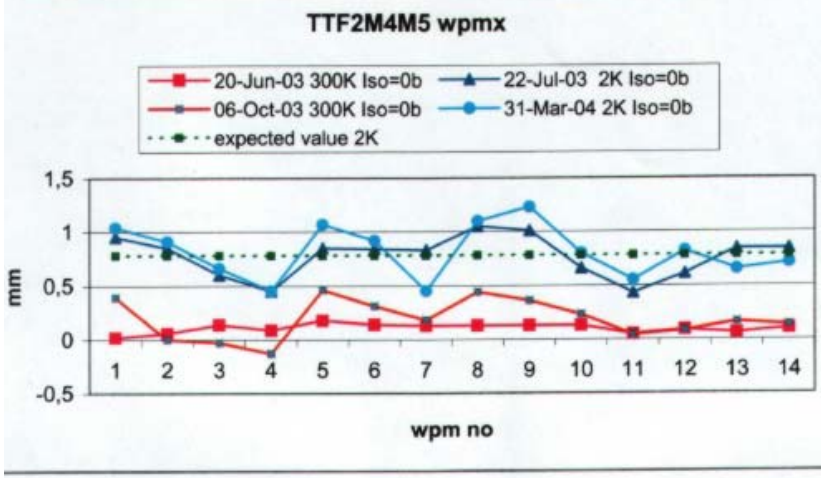

Module 4 & 5

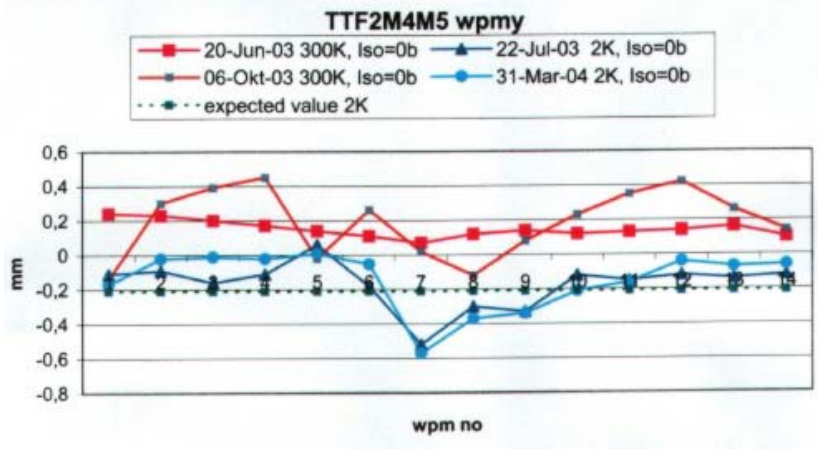
# Safe Cooldown of ACC4 and ACC5



# ACC4 & ACC5 Met Specs





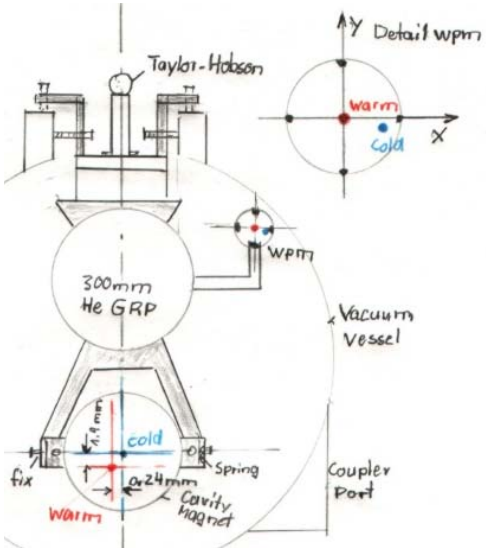
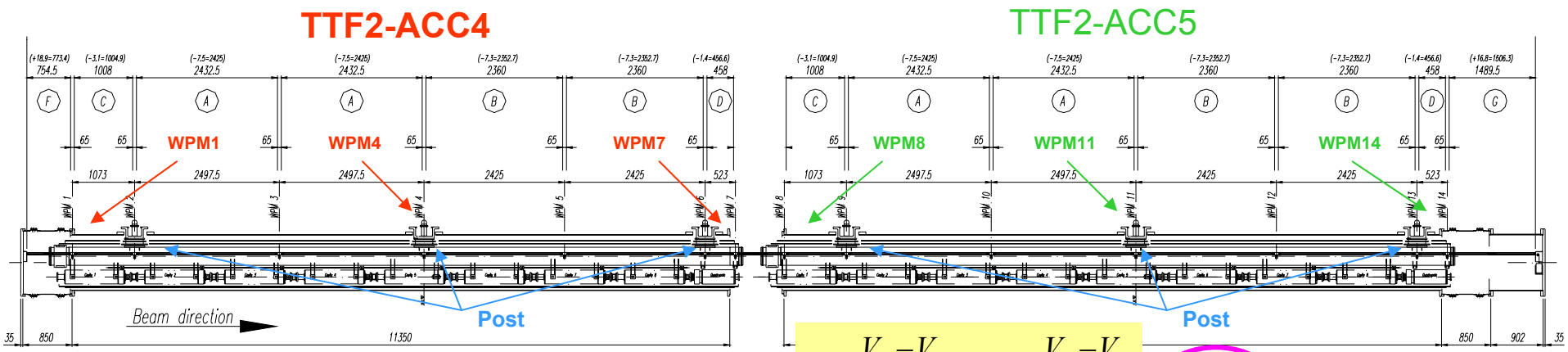




Table 1: Result Summary.

| | | |
|---|---|---|
| **TDR Specifications (rms)** | | |
| Cavities | x/y | ± 0.5 mm |
| Quadrupoles | x/y | ± 0.3 mm |
| **WPM results (peak)** | | |
| Cavities | x | + 0.35/- 0.27 mm |
| | y | + 0.18/- 0.35 mm |
| Quadrupoles | x | + 0.2/- 0.1 mm |
| | y | + 0.35/- 0.1 mm |

- Still some work at the module interconnection
- Cavity axis to be properly defined

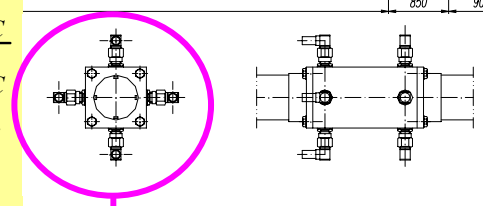
# WPM as Vibration Sensors

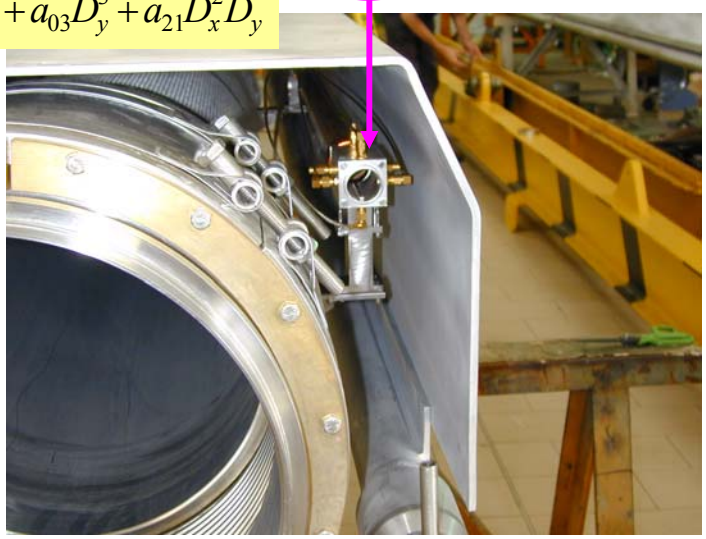



$$D_x = \frac{V_B - V_D}{V_B + V_D} \qquad D_y = \frac{V_A - V_C}{V_A + V_C}$$

$$x = a_{10} D_x + a_{30} D_x^3 + a_{12} D_x D_y^2$$

$$y = a_{01} D_y + a_{03} D_y^3 + a_{21} D_x^2 D_y$$



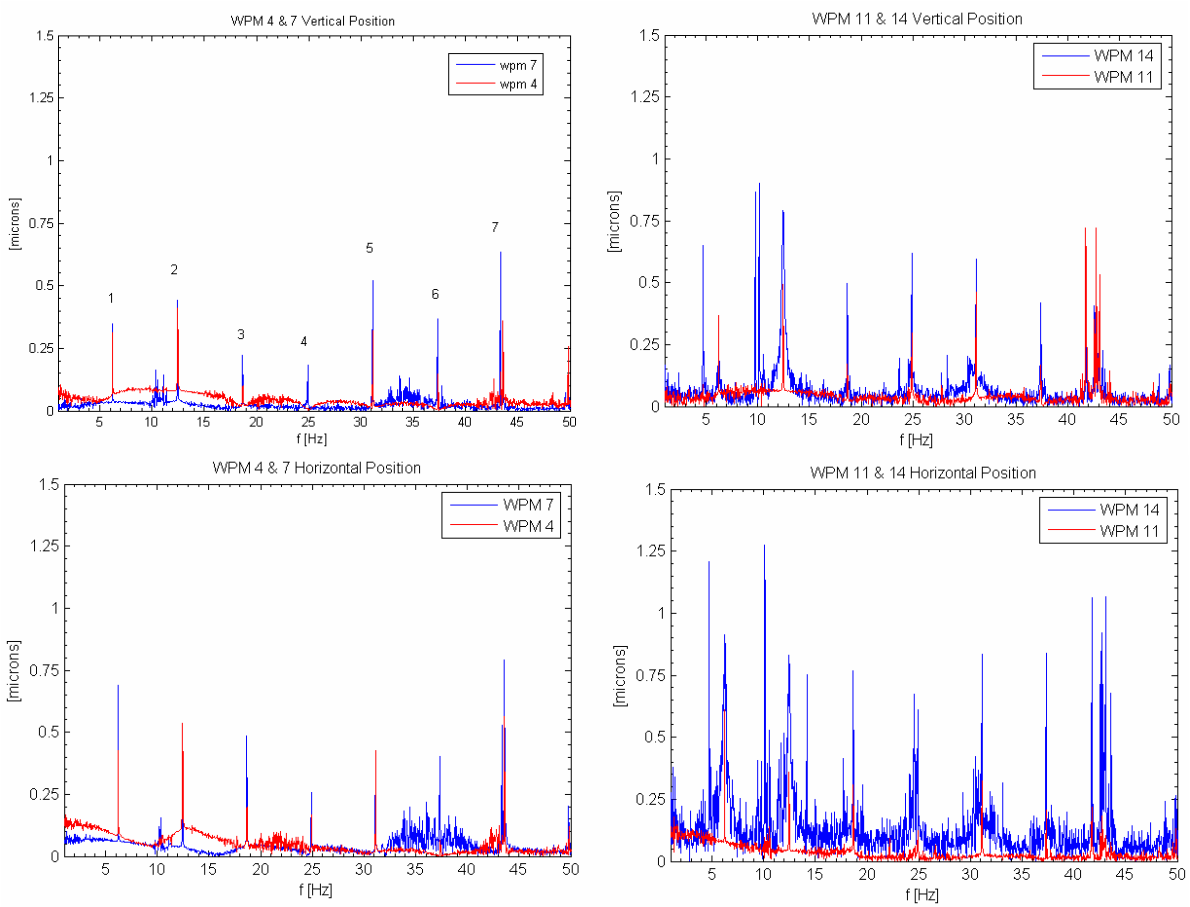


- A WPM is a sort of microstrip four channel directional coupler. A 140 MHz RF signal is applied on a stretched wire placed (nominally) in the center of the monitor bore.
- A Wire Position Monitor (WPM) system has been developed for on-line monitoring of the cold mass during cooldown and operation.
- The low frequency vibrations of the cold mass, amplitude modulate the RF signals picked up by the microstrips.
- The microphonics (and the sub-microphonics) can be recovered de-modulating the microstrip RF signal.

# Preliminary Vibration Spectra

WPMs 4 and 11 are close to the central post: cold mass fix point.

WPMs 7 and 14 are at the end of the corresponding cryomodules.




We have preferred to not filter completely the wire oscillation lines to not suppress useful information.

Looking to WPM 14, a significant amount of noise is present between 10 Hz and 30 Hz, 30 Hz and 40 Hz, due to the proximity of vacuum pumps and similar devices, and under 10 Hz, possibly due to the cryogenic system.

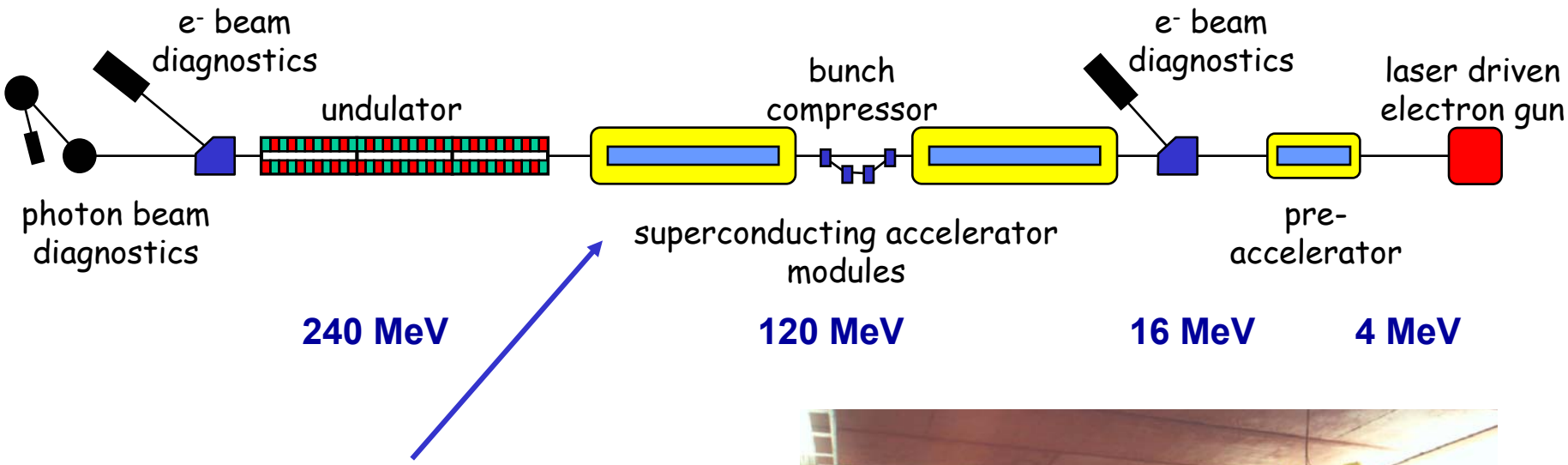
On the contrary, the spectra of the WPM 11 signals, which is at the central post position, shows only the harmonics (filtered) of the wire oscillations.

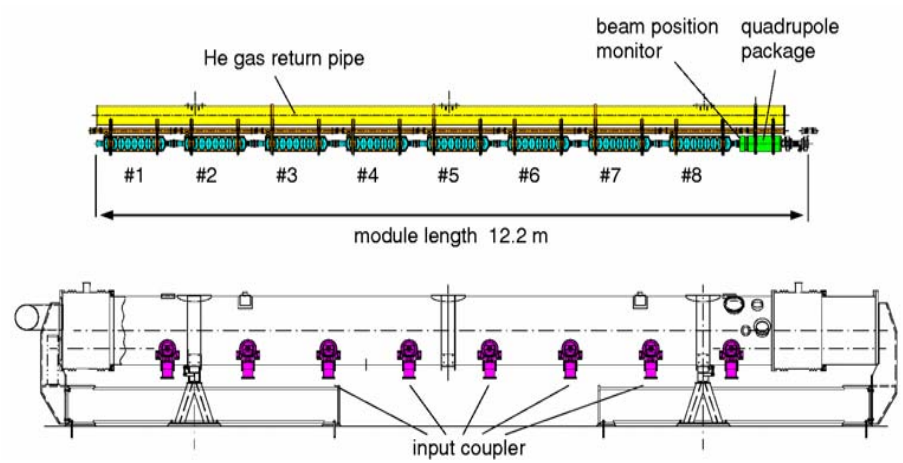
# Module Assembly

The module assembly is a well defined and standard procedure.

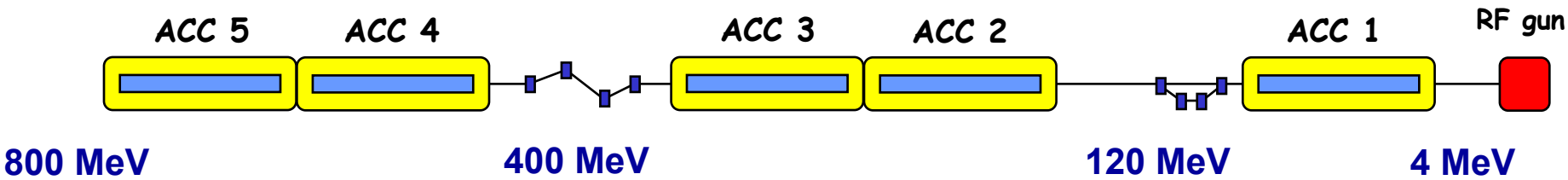
- experience of 10 modules exists
- the latest generation (type III) will be used for series production (XFEL requires 120 modules)
- several cryogenic cycles as well as long time operation were studied
- the assembly problems occurred are well understood and cured

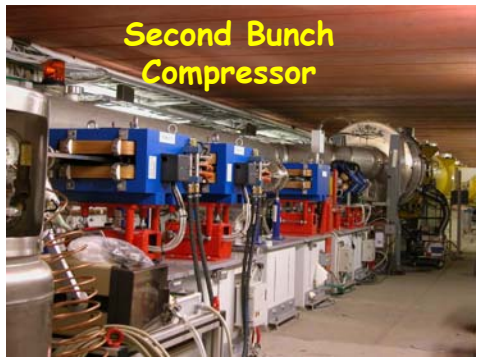
# The TTF I Linac – 6 Year exp.



# TTF II Commissioned





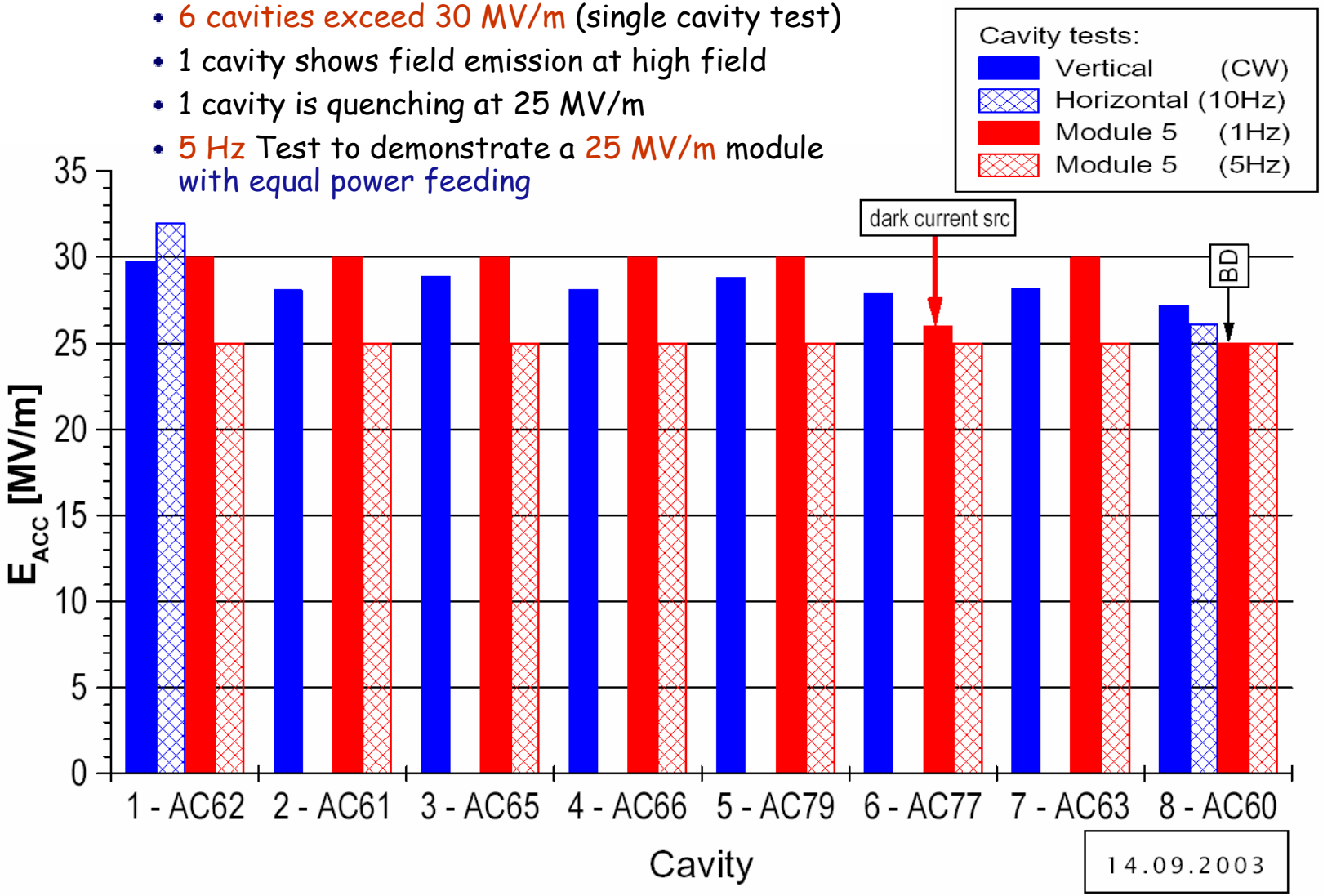

## VUV FEL User Facility

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

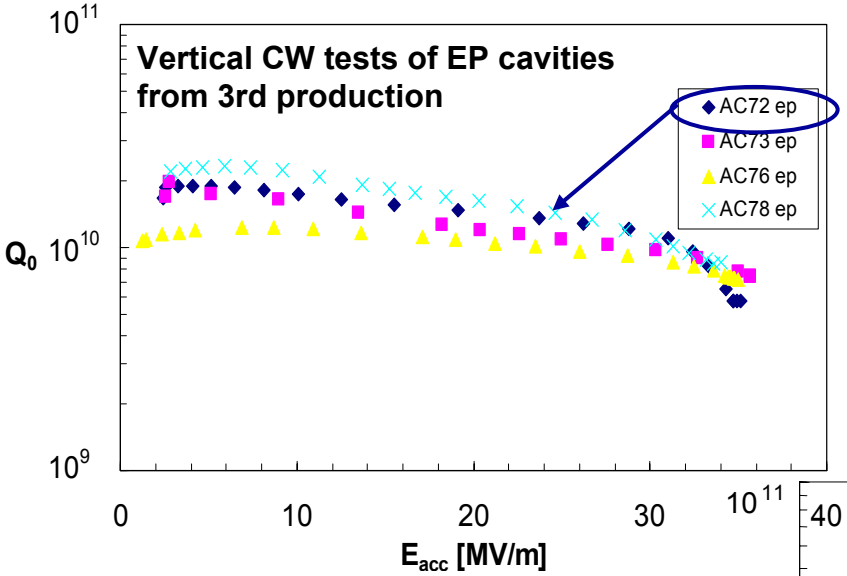
# RF results in module # 5

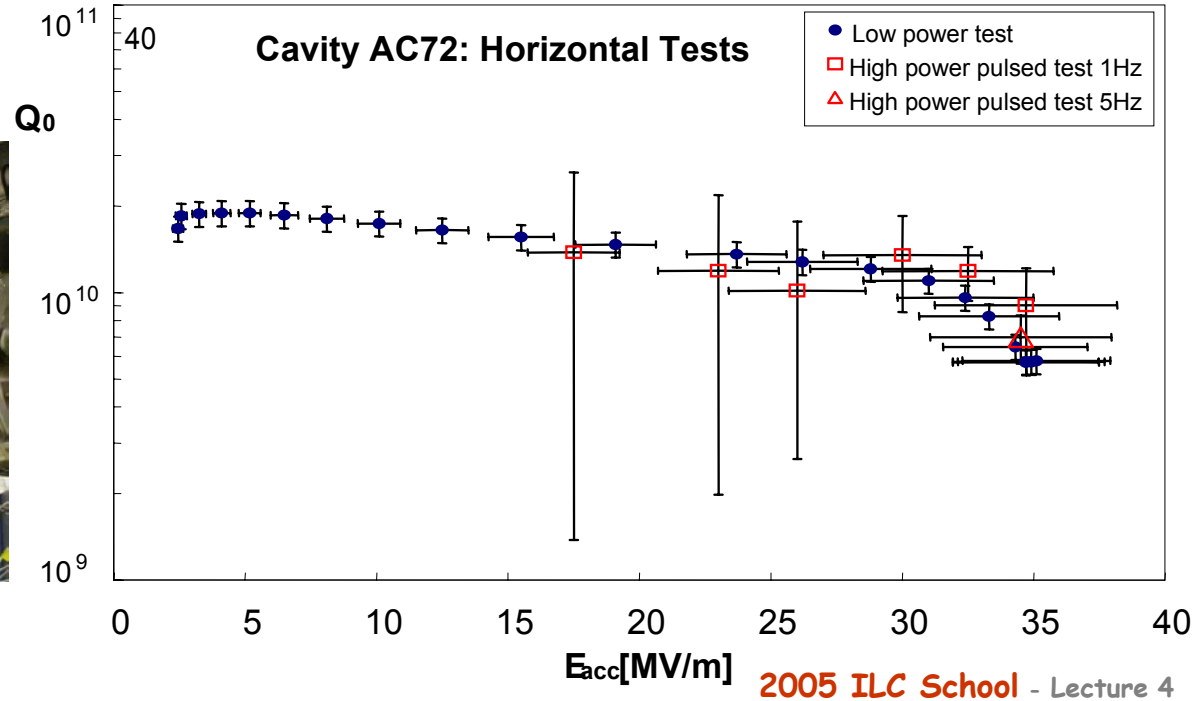
## BCP Cavities

- 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



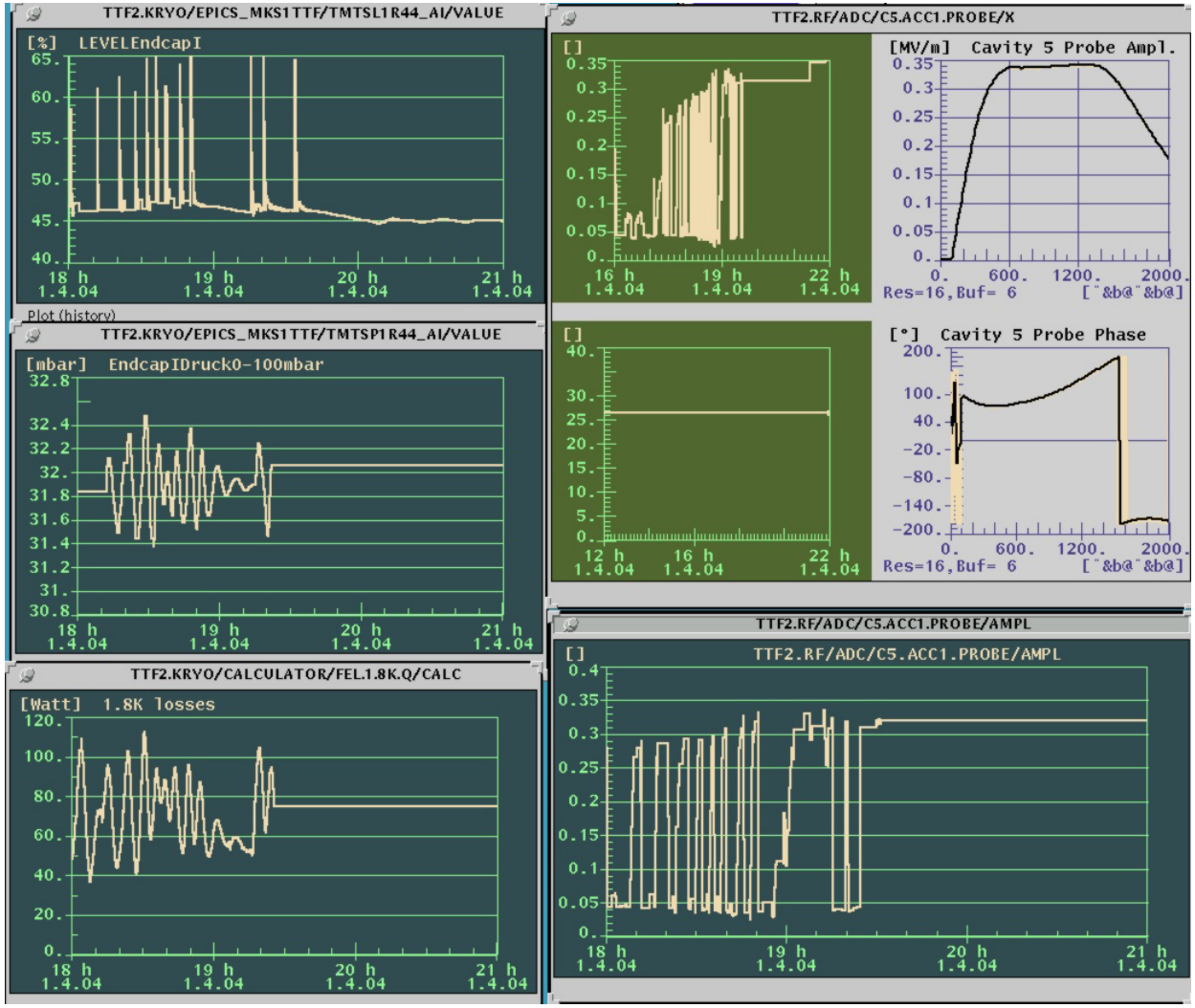
# EP Cavity Test inside a Module





# April 1st 2004

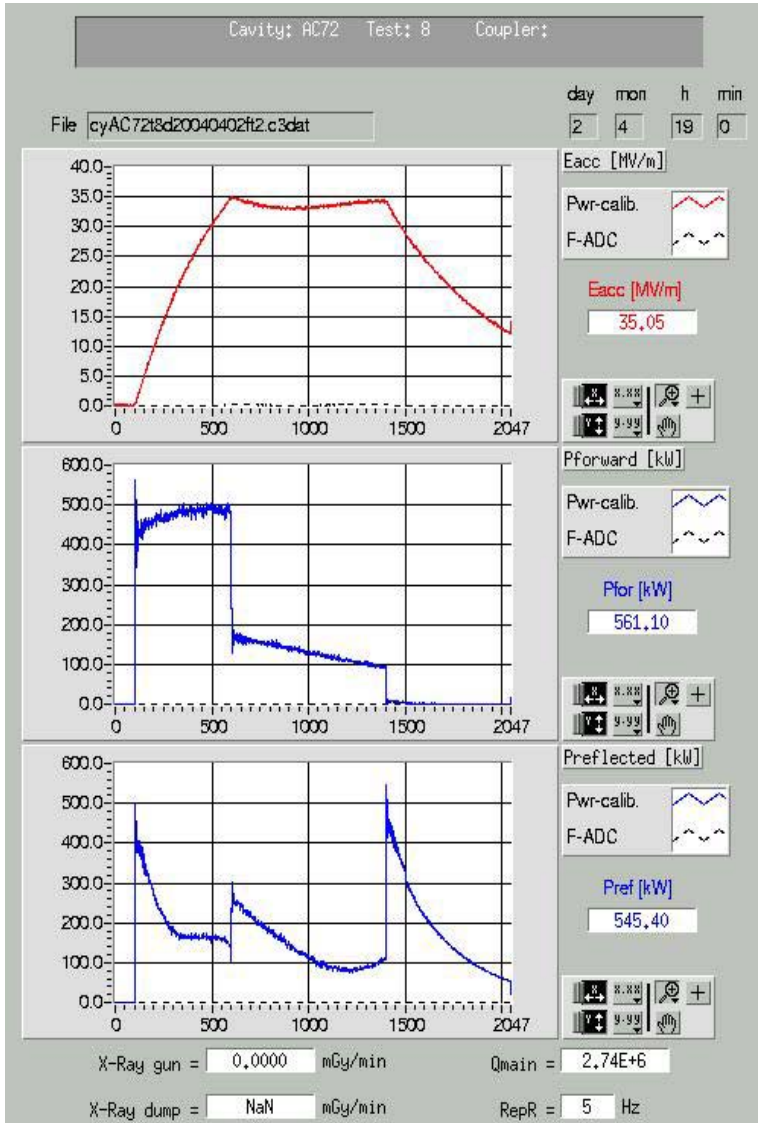
- Very fast conditioning of cavity and coupler
- Full pulse length (800 μs flat top) and 5 Hz repetition rate easily achieved
- Quenches easily detected and recovered
- With just feedforward for Lorentz force detuning compensation AC 72 was stably operated for several hours
- Feedback successfully tested



# Summary of AC72 Test in ACC1

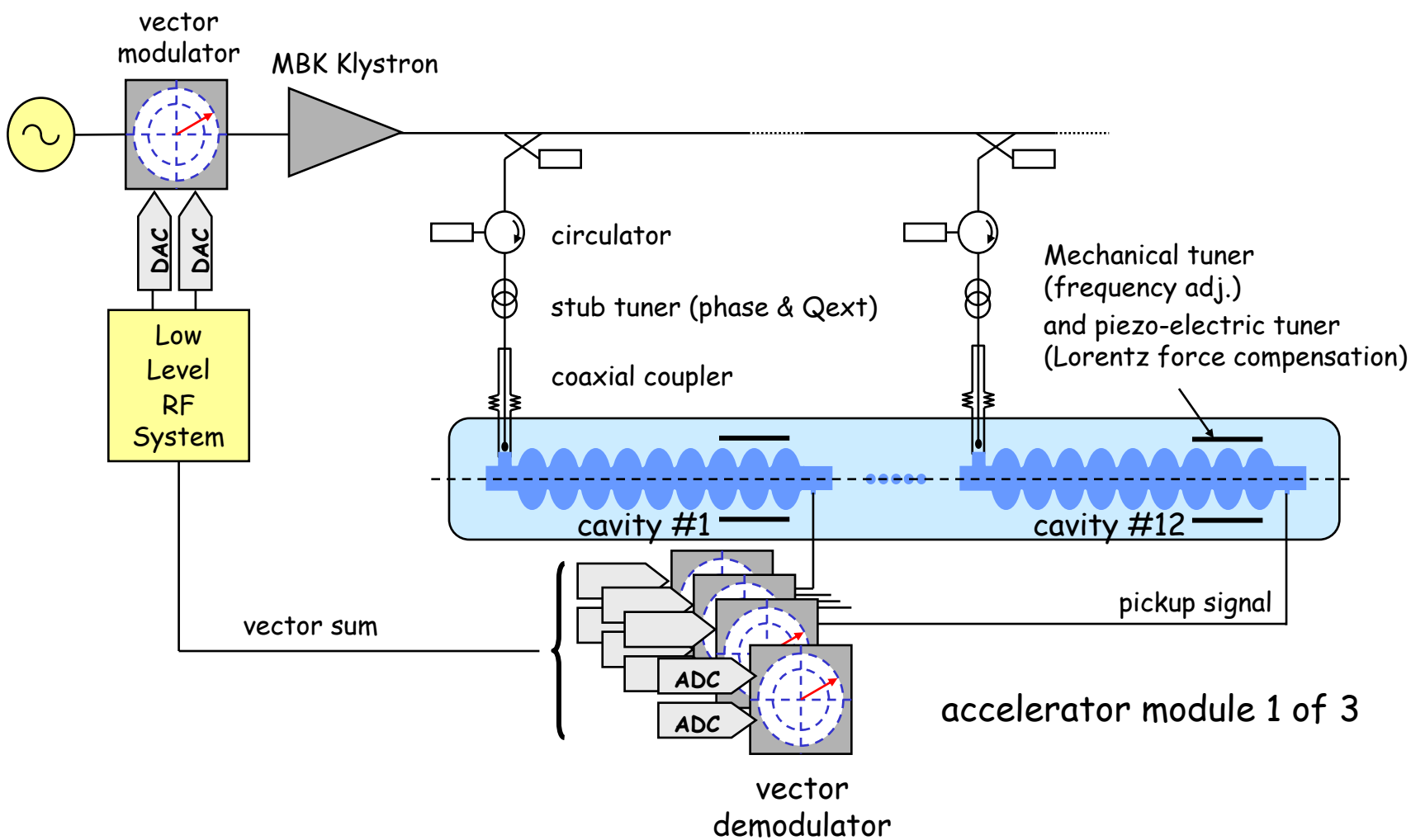
- One of the Electropolished cavities (AC72) was installed into the module ACC 1 for the VUV-FEL
- Cooldown of the LINAC finished on March 31st
- Cavity was individually tested in the accelerator with high power RF
- **Result:**

  **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.



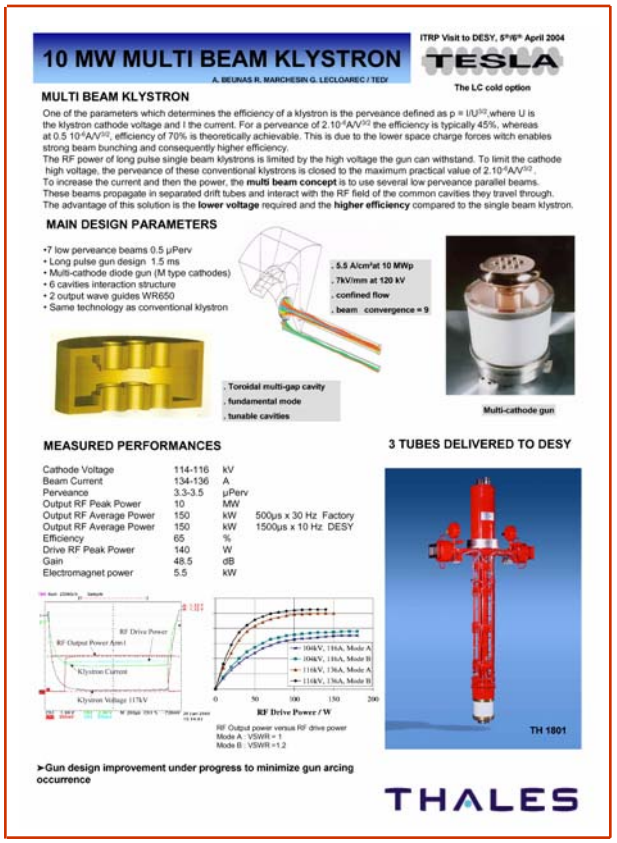
# THE TESLA RF Unit

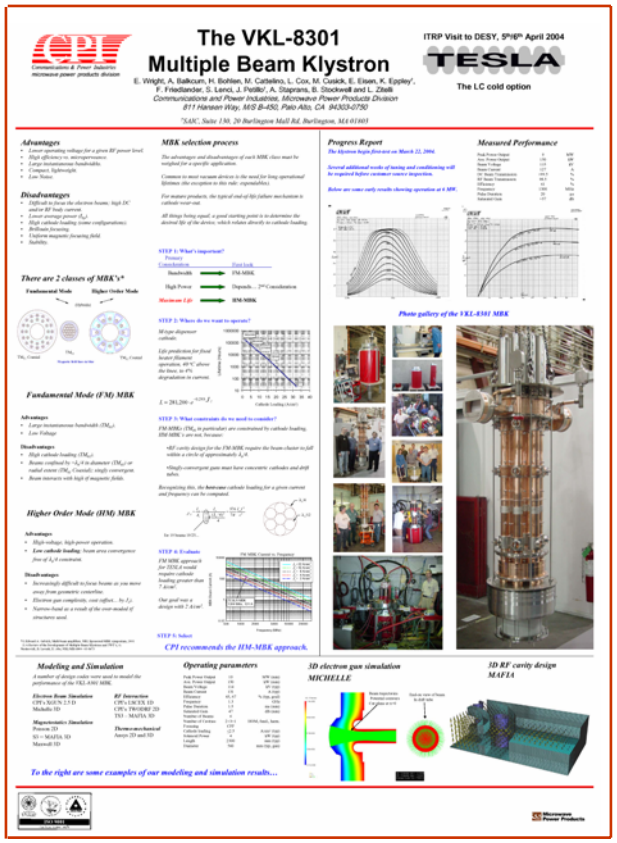
## 1 klystron for 3 accelerating modules, 12 nine-cell cavities each

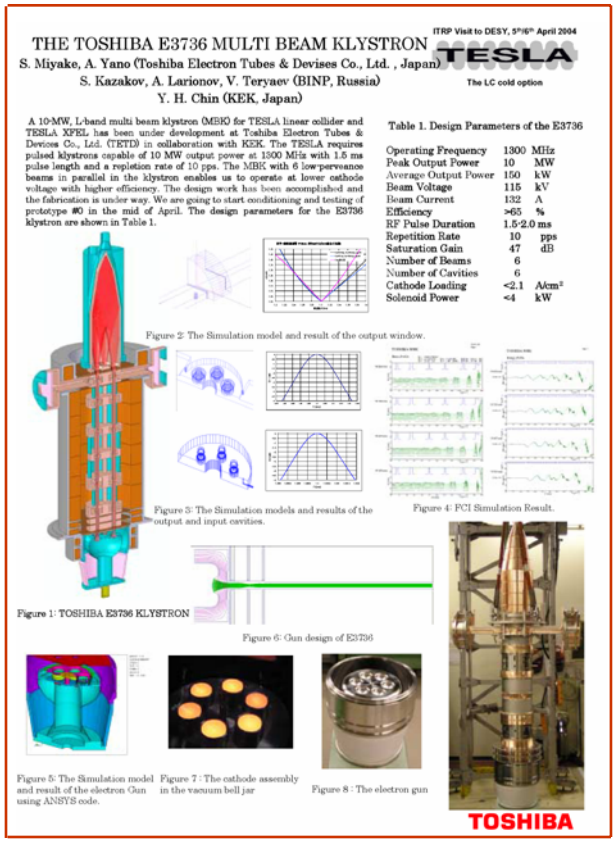


# TESLA Multi Beam Klystrons

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



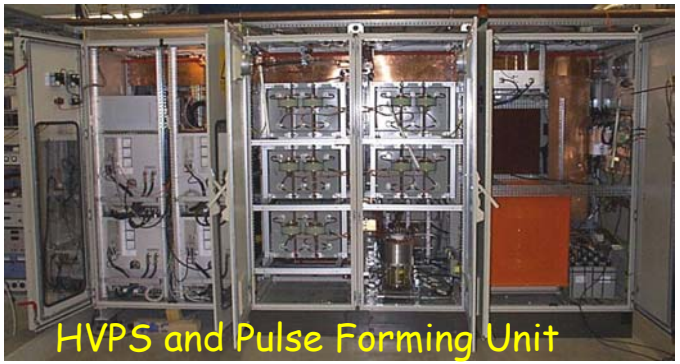

Representatives of: Thales, CPI and Toshiba participated with posters to the ITRP visit to DESY

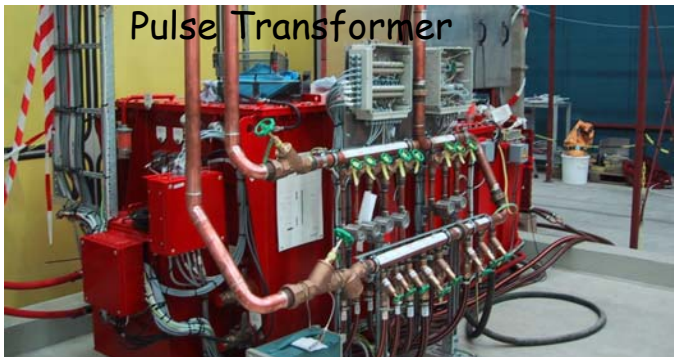
# Modulators are not a concern

## 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



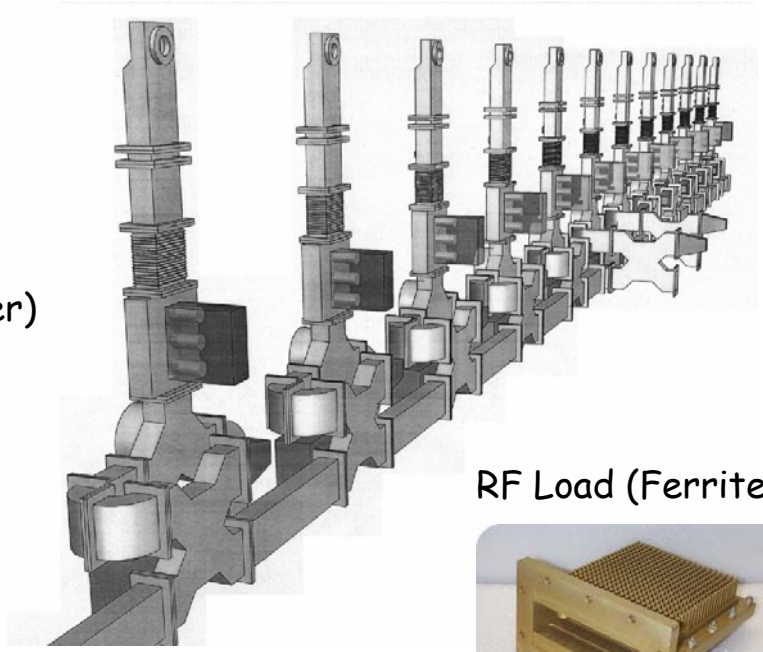
# RF Waveguide Components

**All standard components – Technology well established – Produced by Industry**

3 Stub Tuner (IHEP, Bejing, China)

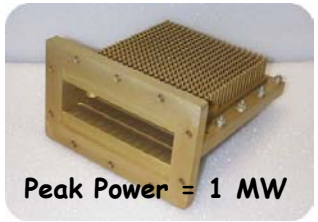
E and H Bends (Spinner)

Circulator (Ferrite)

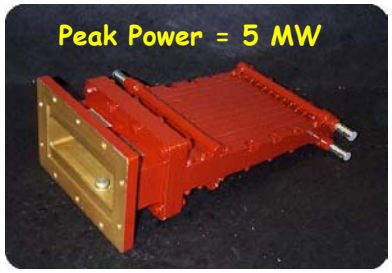


Hybrid Coupler (RFT, Spinner)

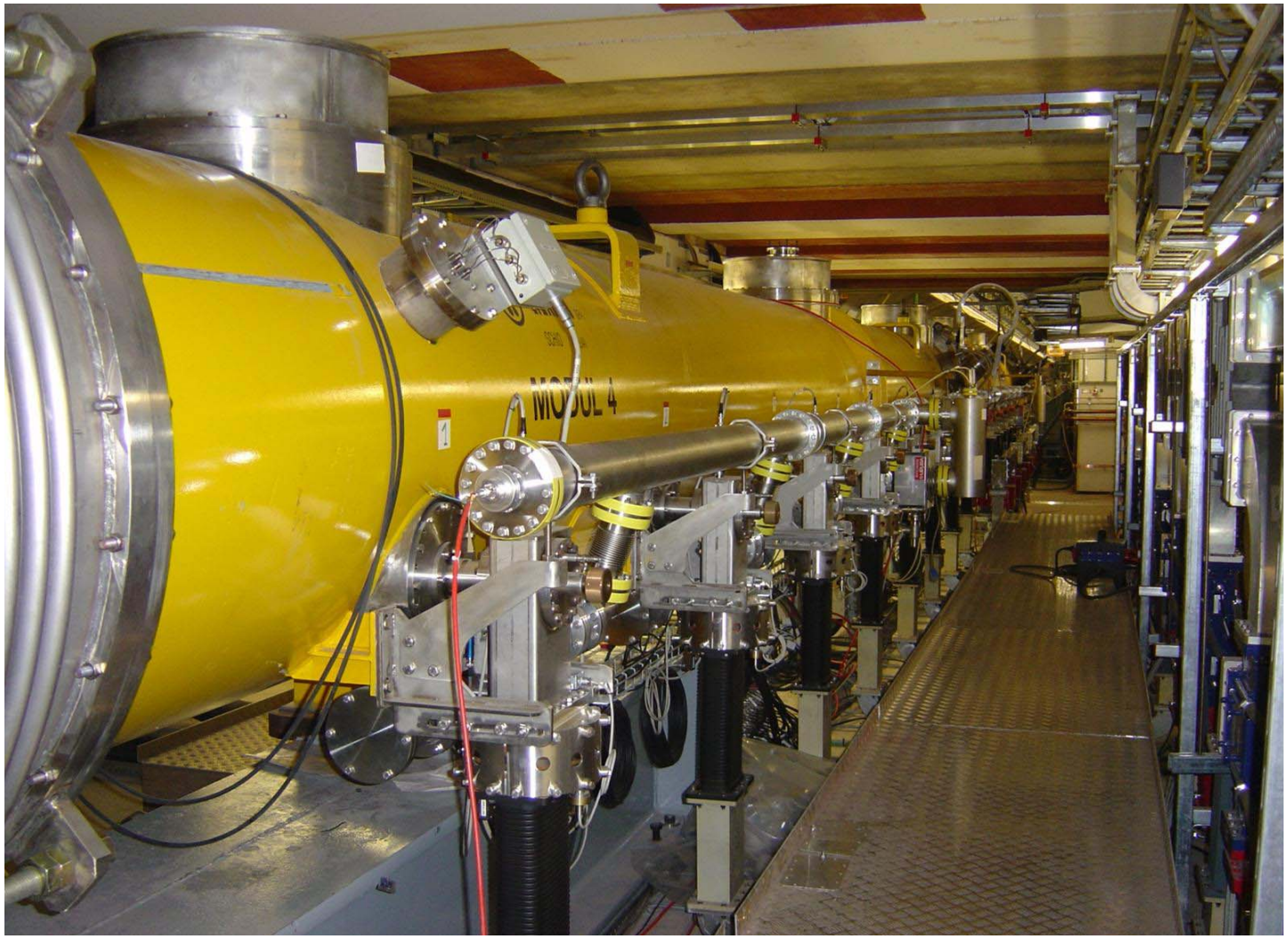
RF Load (Ferrite)




RF Load (Ferrite)

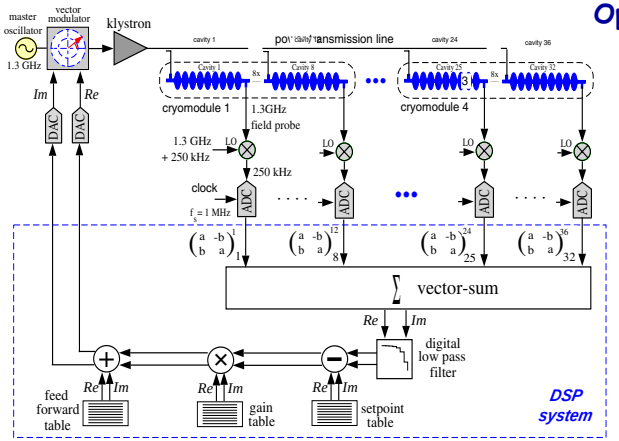


# RF Distribution of Module # 4

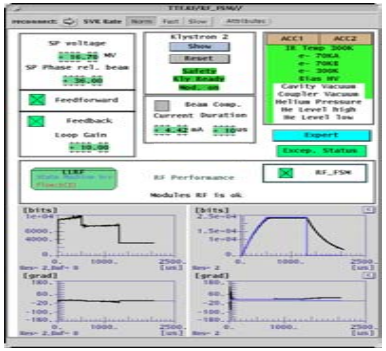


# LLRF performance in TTF

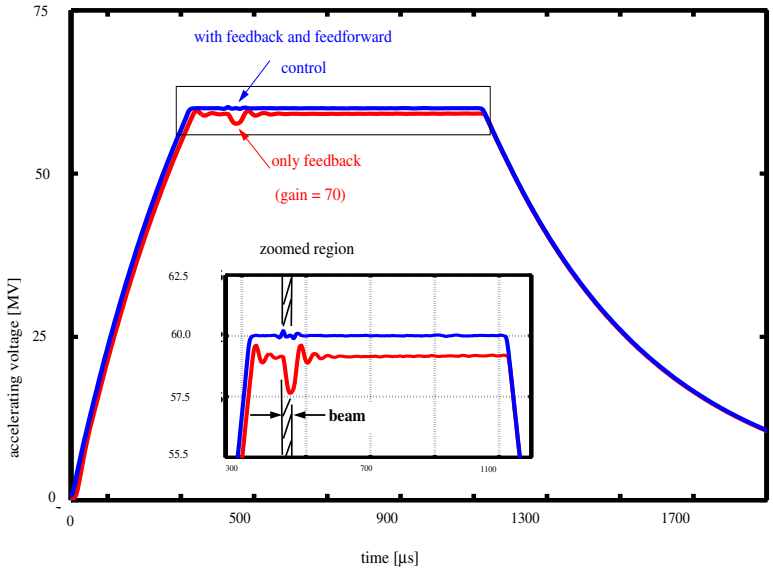
### Principle of RF Control




### 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

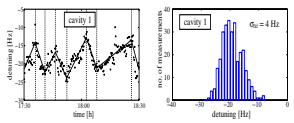


Figure 2: Fluctuations of the cavity resonance frequency. a) Slow drifts over a period of one hour and b) probability density of the cavity resonance frequency with an rms width of 2Hz - 7Hz.

### Lorentz Force Detuning

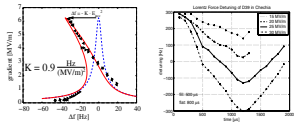
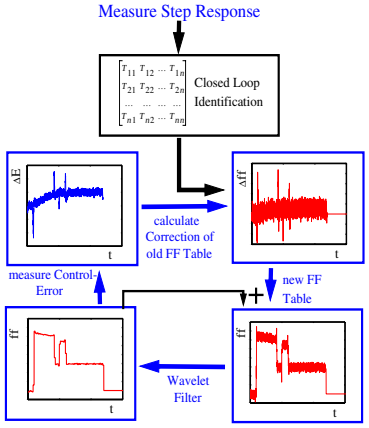


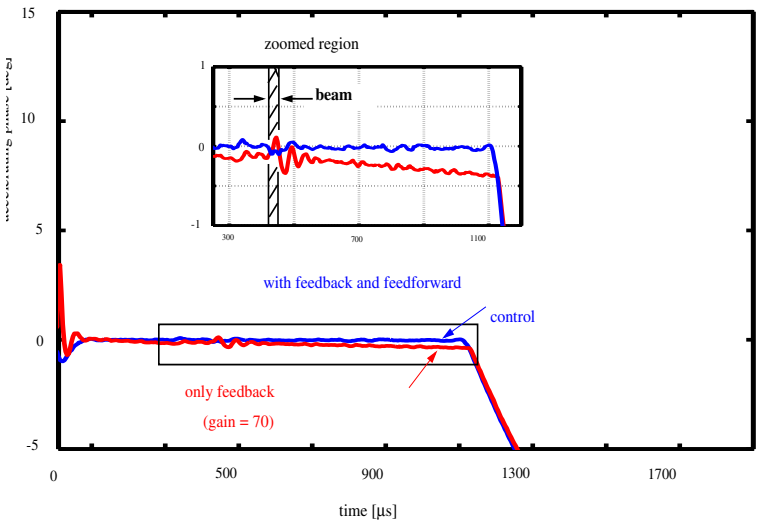
Figure 3: Influence of radiation pressure on the resonance curve of a sc cavity. a) Static detuning during cw operation and b) dynamical detuning during nominal TESLA pulse.

### Adaptive Feedforward




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

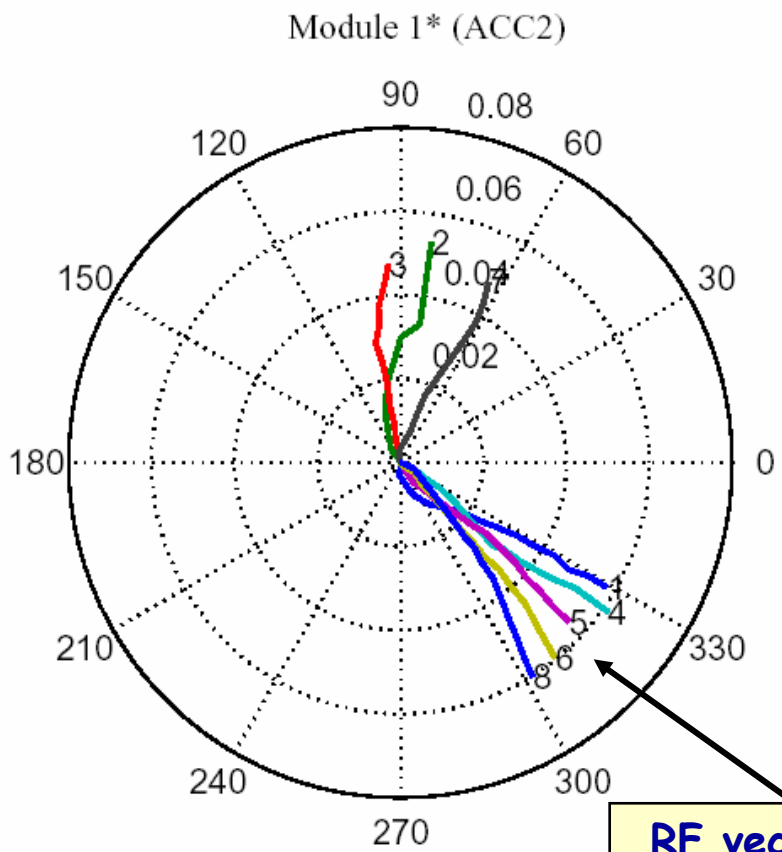
**The calculation of a new feed forward table needs only a few seconds.**



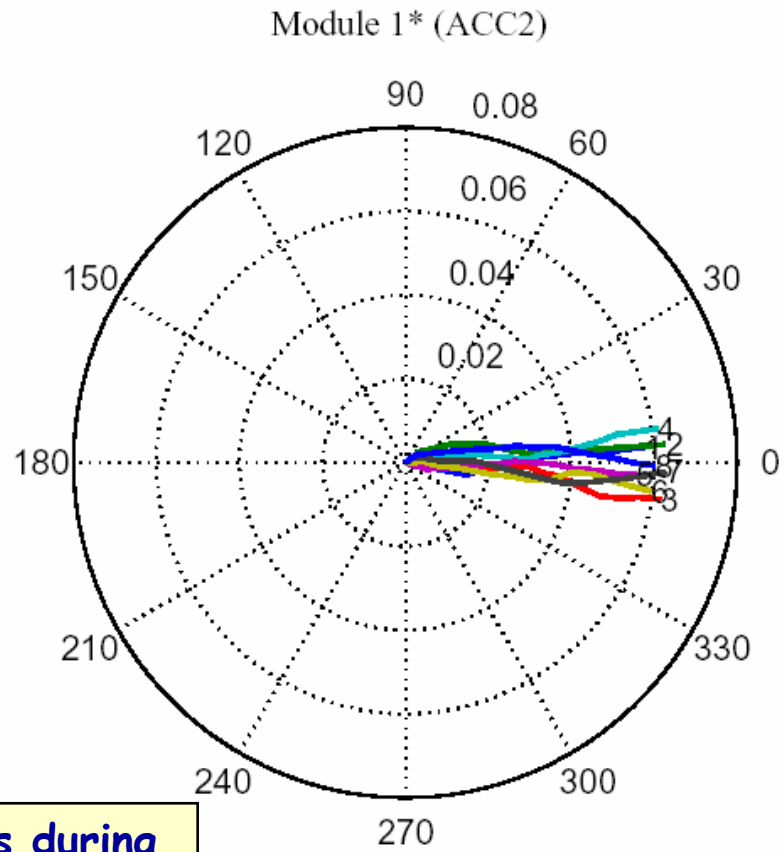
# LLRF: Operation Example

## Phase Adjustment Using Beam Transients

**before adjustment**




**after adjustment**

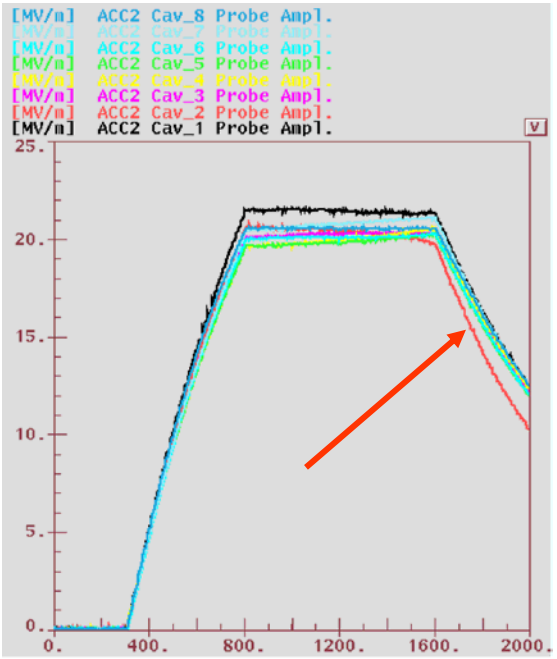


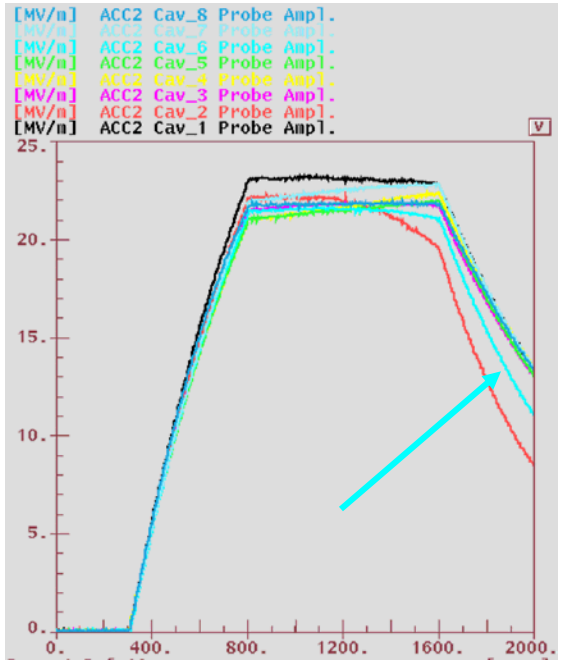

**RF vectors during 800 μs flat top**

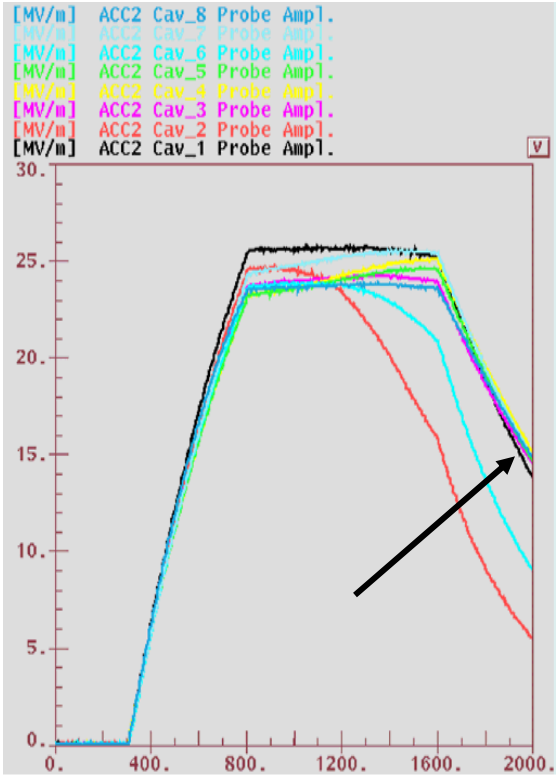
# LLRF: Operation Example

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

# Global SCRF Test Facilities

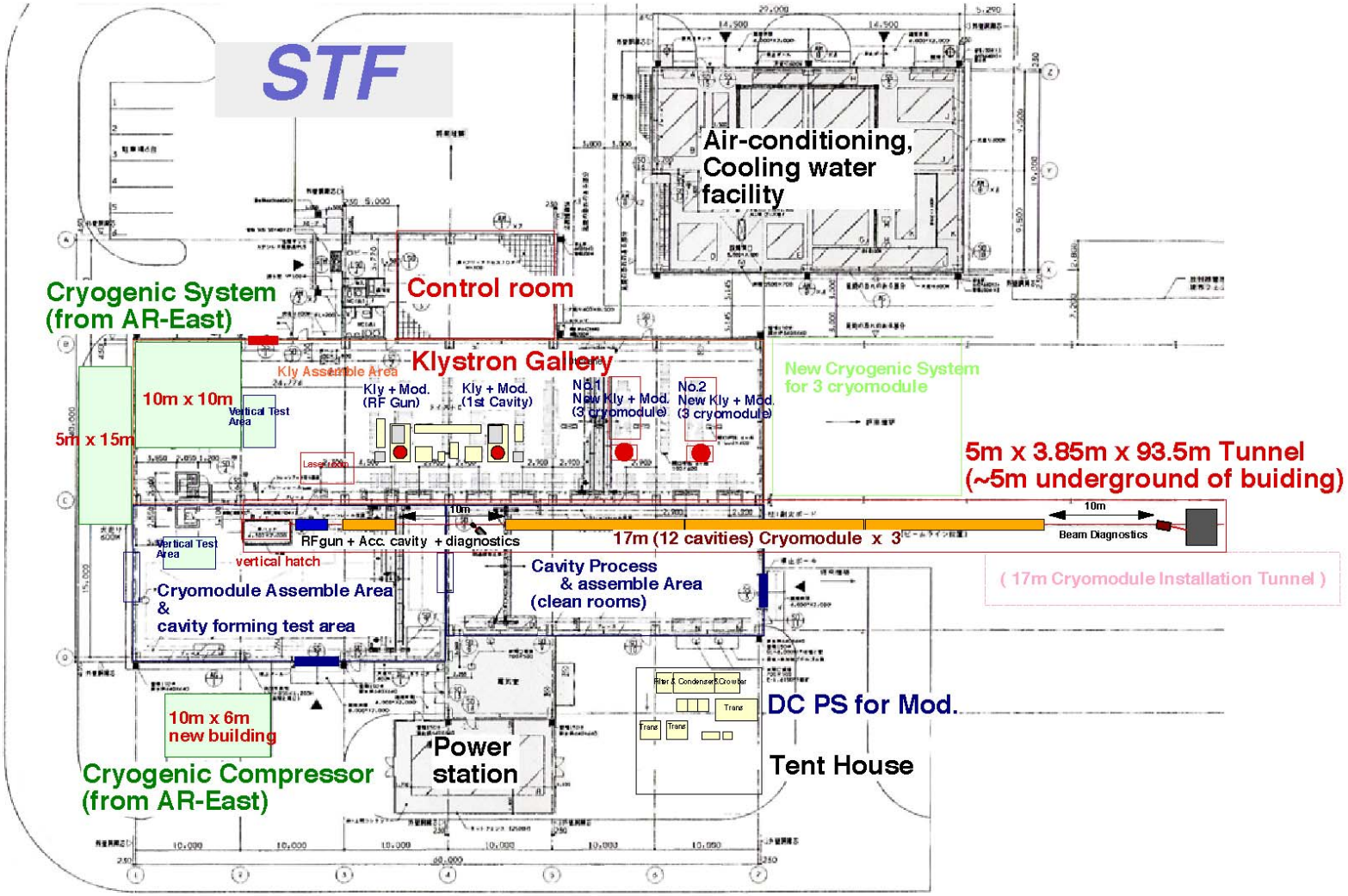
- **TESLA Test Facility (TTF) @ DESY**
  currently unique in the world
  VUV-FEL user facility
  test-bed for both XFEL & ILC

- US proposed **SMTF @ FNAL**
  Cornell, JLab, ANL, FNAL, LBNL, LANL, MIT, MSU, SNS, UPenn, NIU, BNL, SLAC
  currently requesting funding
  TF for ILC, Proton Driver, RIA (and more)

- **STF @ KEK**
  aggressive schedule to produce high-gradient (45MV/m) cavities / cryomodules

- **Others?**

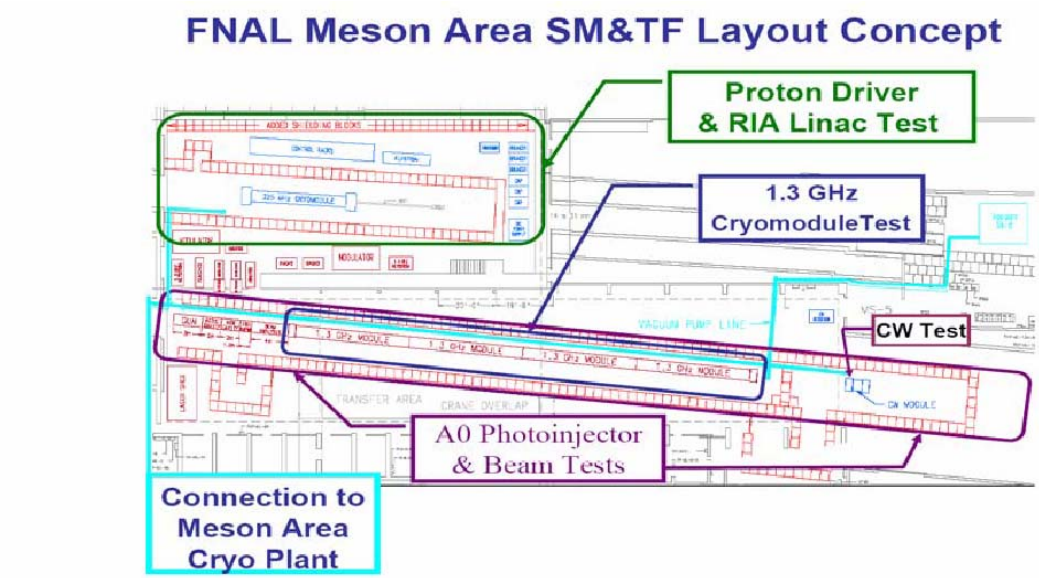
# STF @ KEK

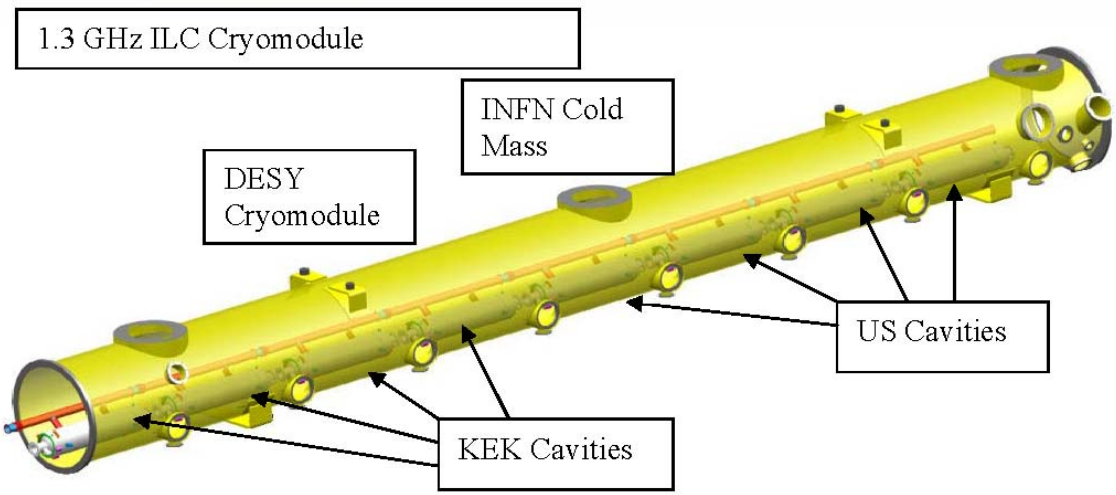



Plan of Superconducting Cavity Test Facility (STF)

V2.1 Hitoshi Hayano, 11/03/2004

# SMTF @ FNAL as presented to DOE




"The **SMTF proposal is to develop U.S. Capabilities** in high gradient and high Q superconducting accelerating structures

in support of

**International Linear Collider**
**Proton Driver**
RIA
4th Generation Light Sources
Electron coolers
lepton-heavy ion collider
and other accelerator
projects of interest to U.S
and the world physics
community."

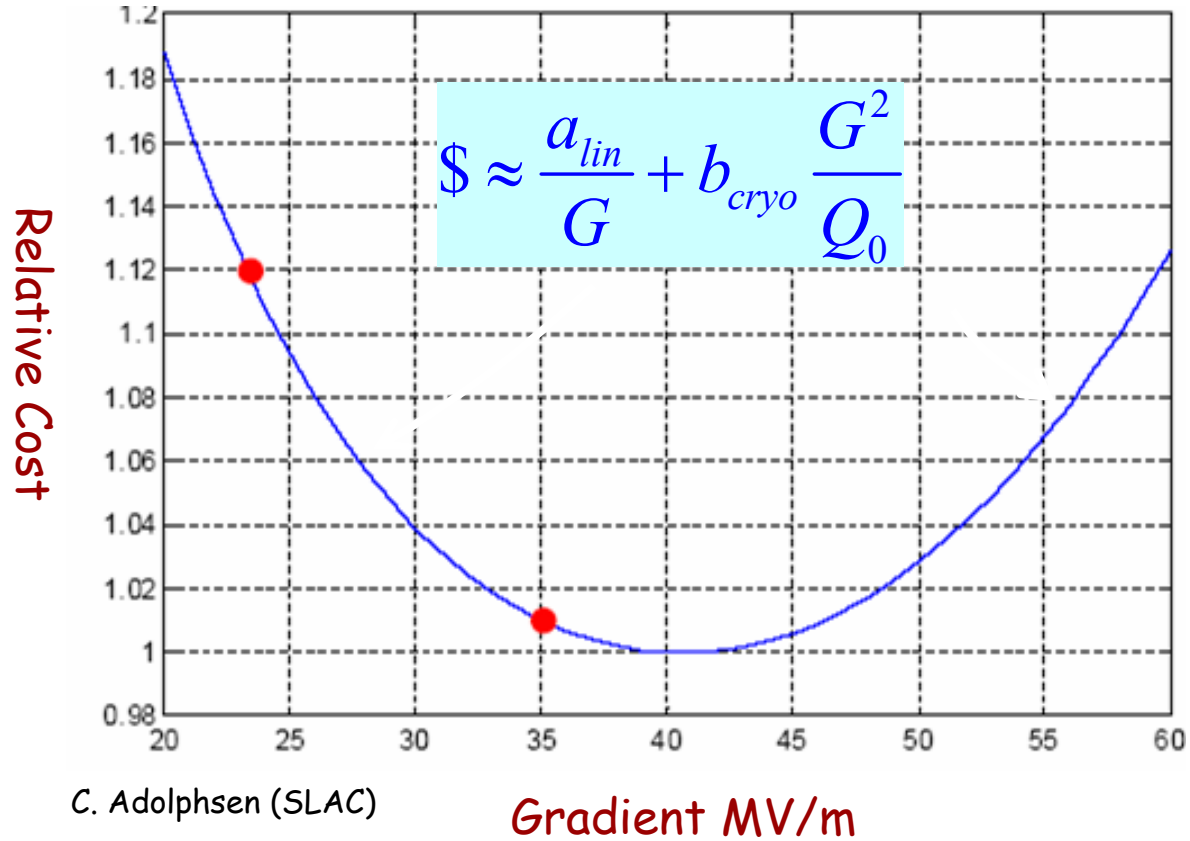
# Main Linac: The Cost Driver

- Main Linacs are the biggest single cost item
- 10 years of R&D by the TESLA collaboration has produced a mature technology
  - But we're not quite there yet…
- Primary focus of future R&D *should* be
  - successful tech. transfer to industry
  - cost reduction through industrialisation
  - need extensive effort to achieve high reliability !!!
- XFEL project is already doing much of this within Europe
- Within 'brave new ILC world', there is still room for discussion
  - One important question:
    "What should the design gradient be?"

# About the Gradient for ILC

- 35MV/m is close to optimum
- 30 MV/m would give safety margin

Japanese are pushing for 40-45MV/m

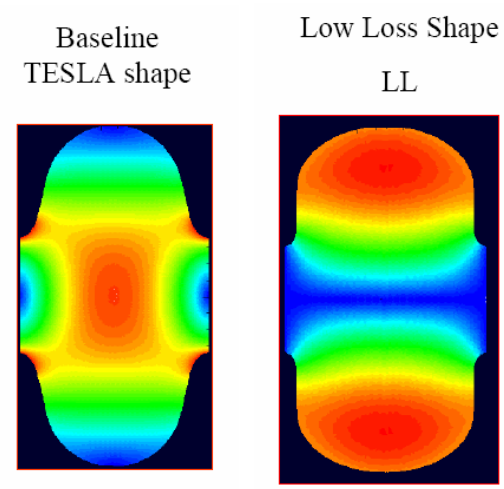



C. Adolphsen (SLAC)

"ICHIRO" cavity

Larger magnetic volume

Lower peak magnetic field



# 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 can be cured**,
- TESLA Technology is widely distributed and its basics are on hands
- **Industry has already most of the required know-how** and technology transfer started.
- **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.
- But **a lot of work is still to be done** for reproducibility, reliability and cost compatible with ILC