Challenges of the ILC Main Linac

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Theme: Power and Precision

Engineering Design for the ILC

- We are at a critical juncture of the ILC.
  - **Two years after the formal formation of the ILC Global Design Effort (GDE),**
  - **the recent completion of the draft Reference Design Report (RDR) marks a major milestone in this truly global effort.**
- Our GDE is now in the process of restructuring itself and making plans for the engineering design phase, leading to the completion of the ILC Engineering Design Report (EDR) in 2010.

Challenges:

- Our Engineering Design strategy and priorities come from the identification, (in the RDR), of scientific and engineering challenges of the ILC.

COST

1. cost of the main linac:

   + associated earthworks and cooling/power systems,

   = 60% of the ILC total cost.

ENERGY

2. achieve the highest practical gradient

   this R & D has the largest cost leverage of any of the ongoing programs.

PRECISION

3. beam dynamics and beam tuning processes in the main linac,

   we will not have the opportunity to do full (or even large) scale tests of these before construction

ILC → Superconducting RF

- On 20 August 2004, an international technical panel recommended that the linear collider be based on superconducting RF technology:
- “The superconducting technology has features, some of which follow from the low rf frequency, that the Panel considered attractive and that will facilitate the future design:
  - **The large cavity aperture and long bunch interval simplify operations, reduce the sensitivity to ground motion, permit inter-bunch feedback, and may enable increased beam current.** → Precision
  - **The main linac and rf systems, the single largest technical cost elements, are of comparatively lower risk.** → Risk
  - **The construction of the superconducting XFEL free electron laser will provide prototypes and test many aspects of the linac.** → Testing
  - **The industrialization of most major components of the linac is underway.** → Industrial
  - **The use of superconducting cavities significantly reduces power consumption.** → Power
- “

Superconducting RF

- Luminosity requires beam power & small beams;
  - **Superconducting RF is the most effective way to create high power beams**
- Proven design:
  - **1.3 GHz niobium sheet metal cavities**

POWER

  - **ILC - each cavity delivers 285 KW to 9mA beam (nom)**
  - **ILC - fill time 38% total pulse**
  - **ILC - linac efficiency (RF to beam): 50%**
    - Fill time, distribution and feedback overhead
- Large irises → minimal emittance growth with achievable tolerances

PRECISION

  - **a manageable system**
  - **If we can achieve tighter assembly/tuning tolerances, can improve efficiency**

SCRF linac – basic building block

Figure 1.2-1: A TESLA nine-cell 1.3 GHz superconducting niobium cavity.

- ~ 70 parts electron-beam welded at high vacuum
  - **mostly stamped 3mm thick sheet metal**
- pure niobium and niobium/titanium alloy
  - **niobium cost similar to silver; purification increases cost**
- weight ~ 70 lbs; length ~ 1 m
- 6 flanges

Cavity String Assembly

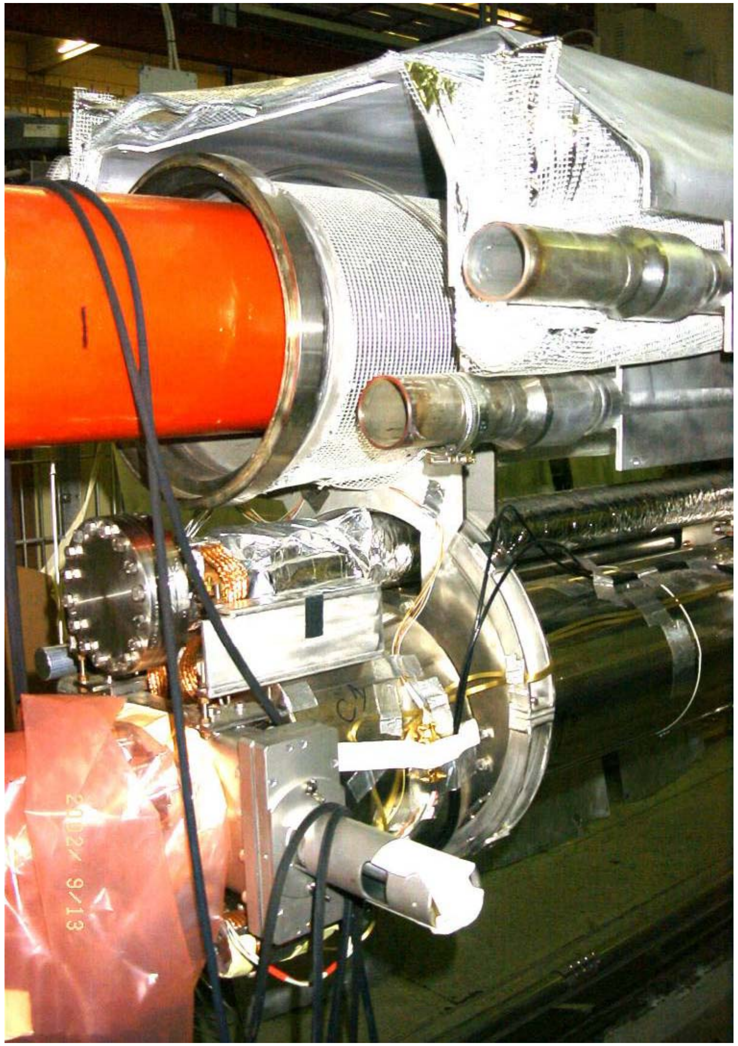
The assembly of an 8 cavity string

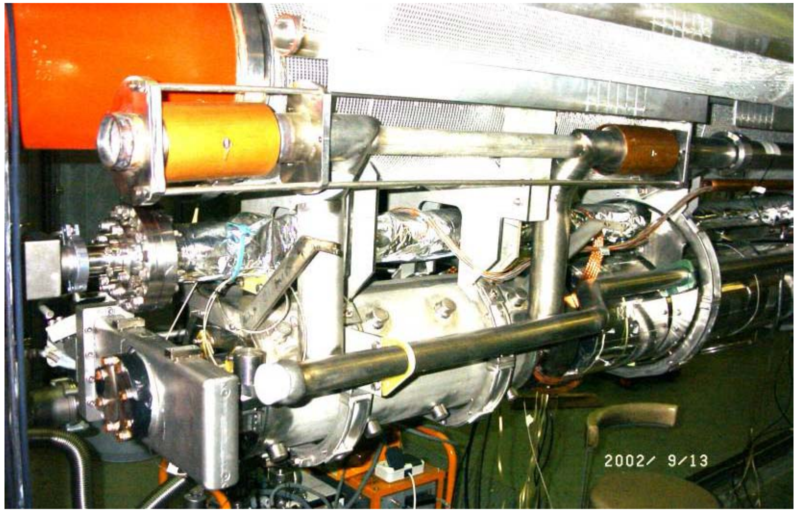
- **is a standard procedure at DESY**
- **was done by technicians from the TESLA Technology Collaboration**
- **was the basis for two industrial studies.**

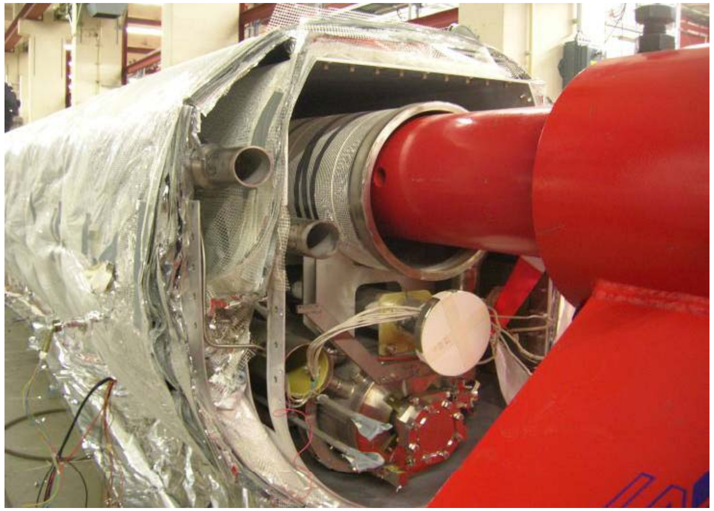
The transfer of this well known and complete procedure to industry has started.

DESY will provide sub-components for the first string / module built in industry; this allows for an early training.

Cryomodule assembly: 1200+ parts



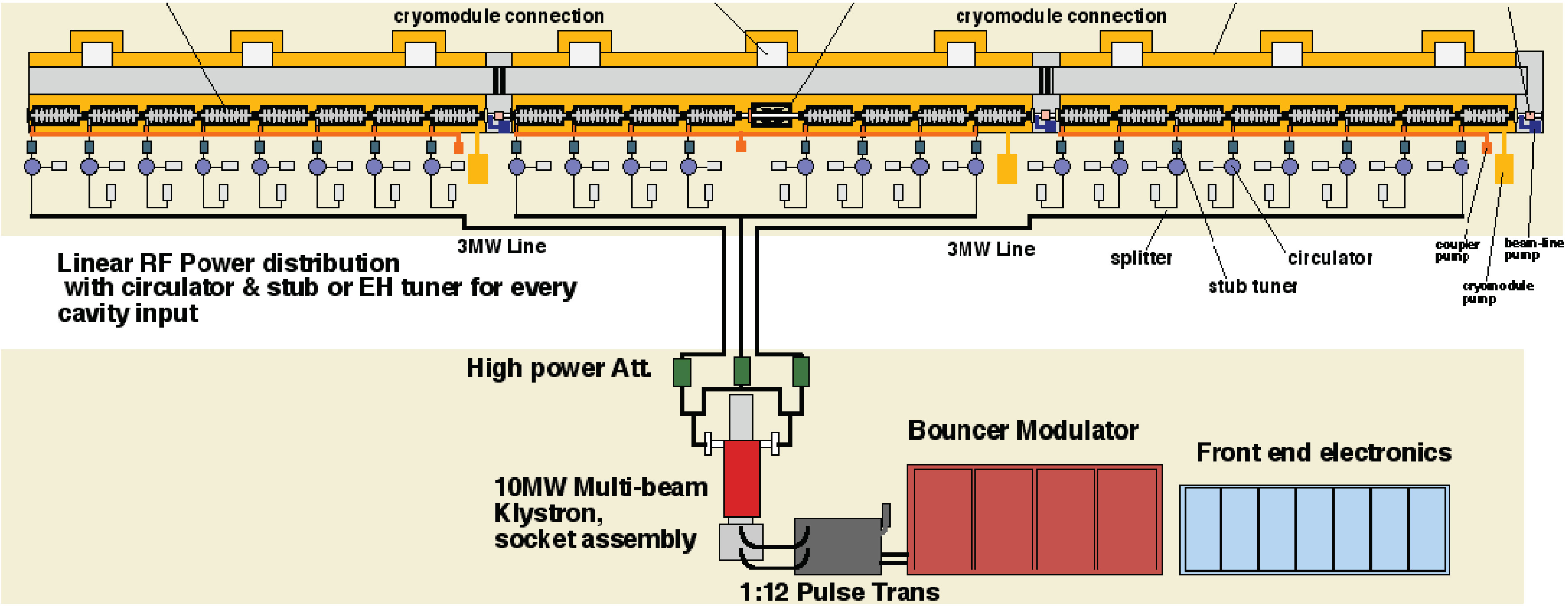




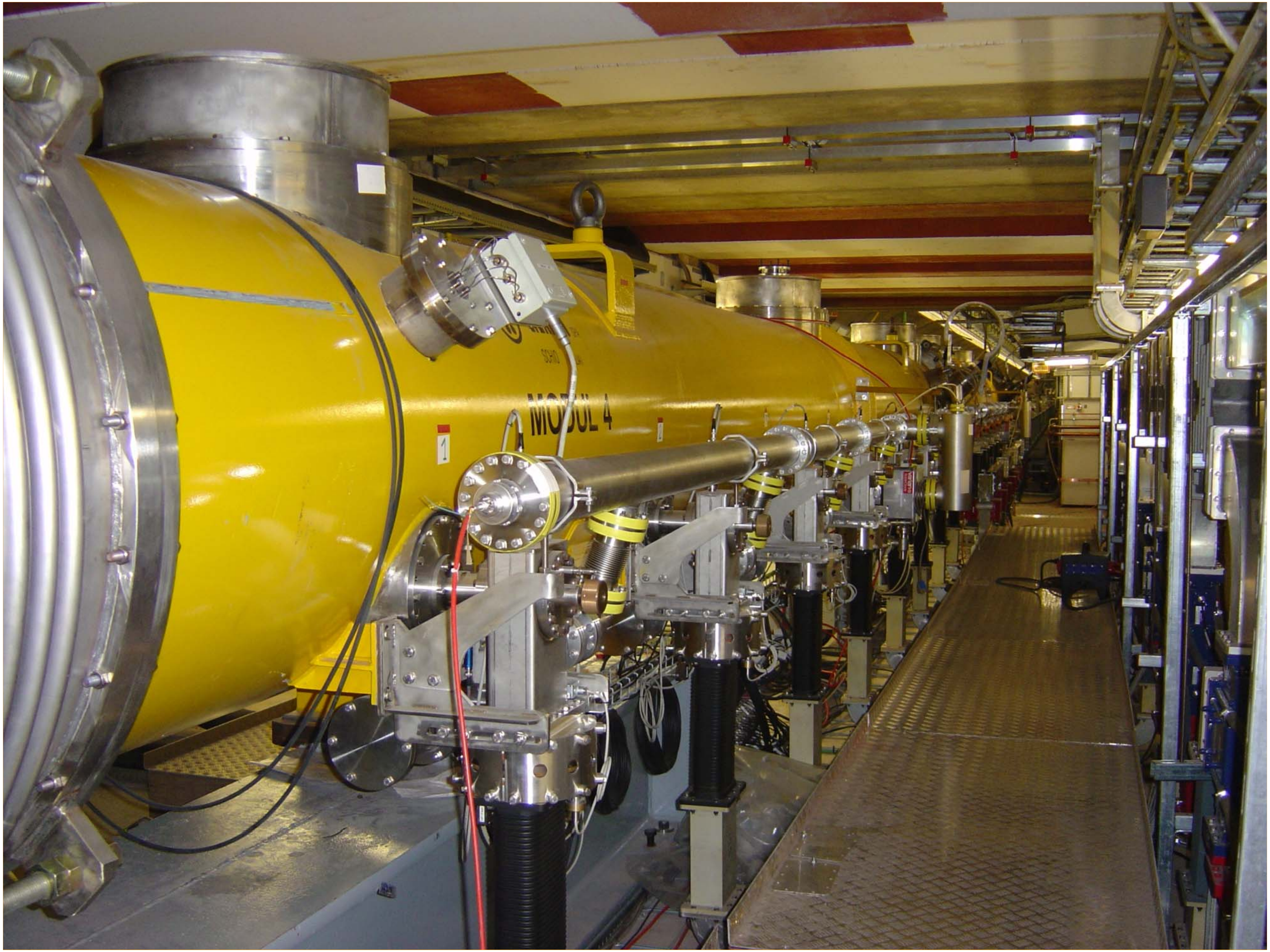
FNAL CM Assembly: T. Arkan

ML basic building block

ILC RF Unit: 3 CM, klystron, modulator, LLRF



Baseline design now has 2 CM with 9 cavities, 1 CM with 8 cavities + quad


MODUL 4
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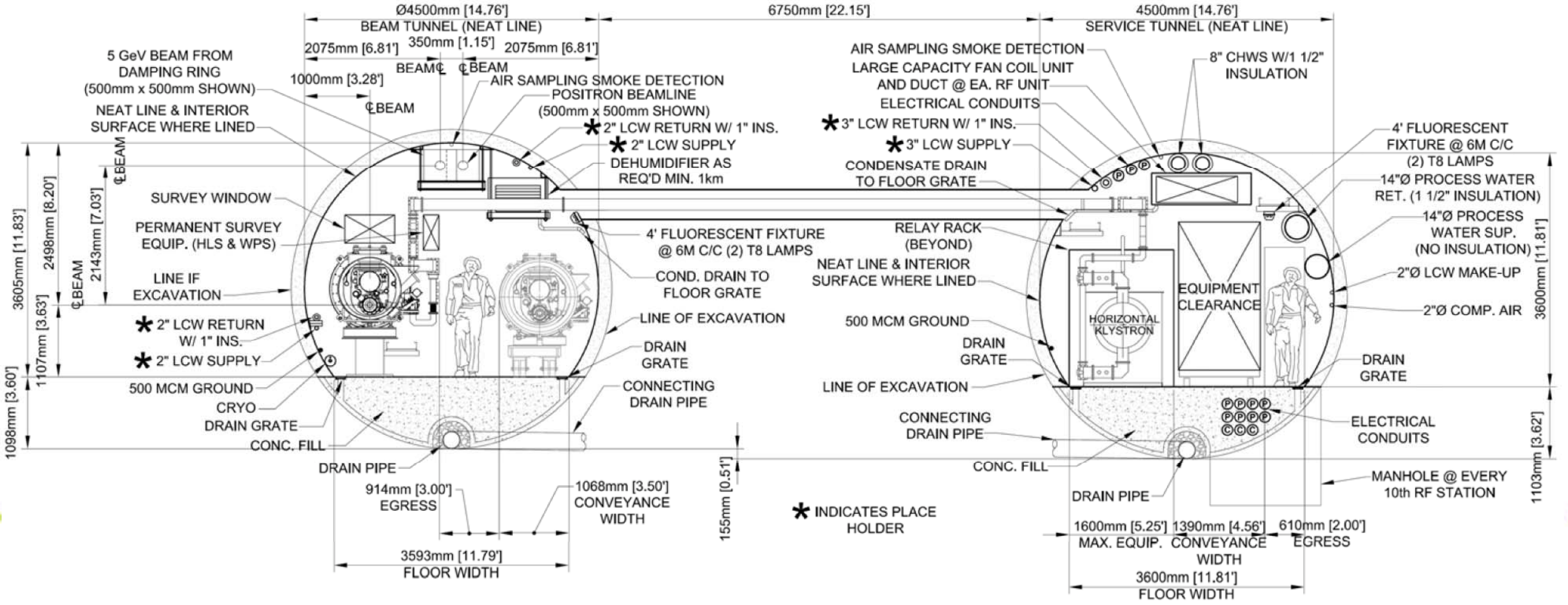
Main Linac Tunnels

- Design based on two 4.5m tunnels
  - **Active components in service tunnel for access**
  - **Includes return lines for BC and sources**
  - **Sized to allow for passage during installation**
  - **Personnel cross-over every 500 meters**



Scale of ILC:

16,088 SC Cavities: 9 cell, 1.3 GHz

1848 CryoModules: 2/3 containing 9 cavities,
1/3 with 8 cavities + Quad/Correctors/BPM

613 RF Units: 10 MW klystron, modulator, RF distribution

72.5 km tunnels ~ 100-150 meters underground

13 major shafts ≥ 9 meter diameter

443 K cu. m. underground excavation: caverns, alcoves, halls

10 Cryogenic plants, 20 KW @ 4.5° K each
plus smaller cryo plants for e-/e+ (1 each), DR (2), BDS (1)

92 surface “buildings” (for Americas’ site), 52.7 K sq. meters

230 M Watts connected power, 345 MW installed capacity

Rdr power parameters / water

- power / water handling scheme is an indicator of design maturity
- Beam power at IP → 10.8 + 10.8 MW
  - **15 % efficient**
  - **10% cooling overhead (100W to remove heat from 1 KW load)**
- Good performance figures – but more to do
  - **TESLA design (2001): ~ 80 MW lower for same luminosity**

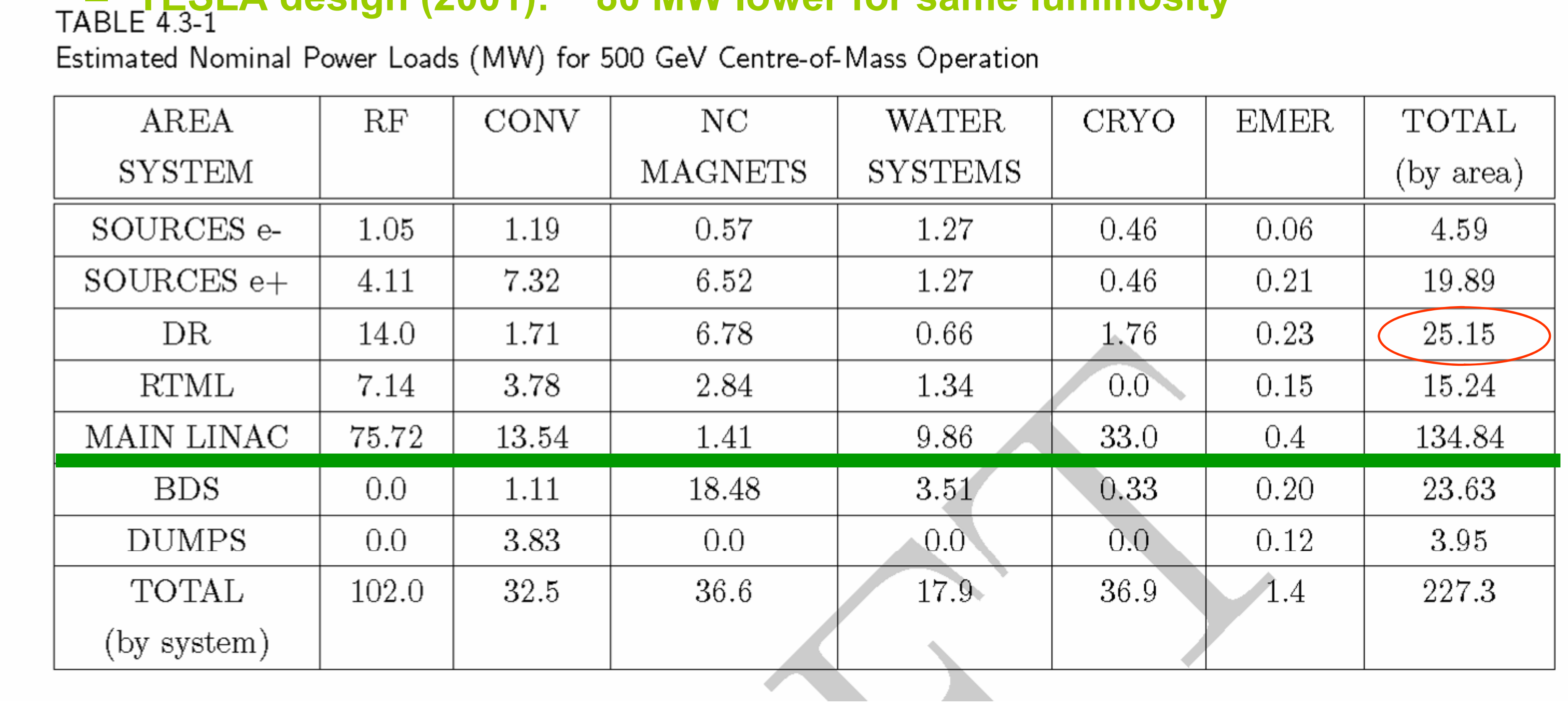
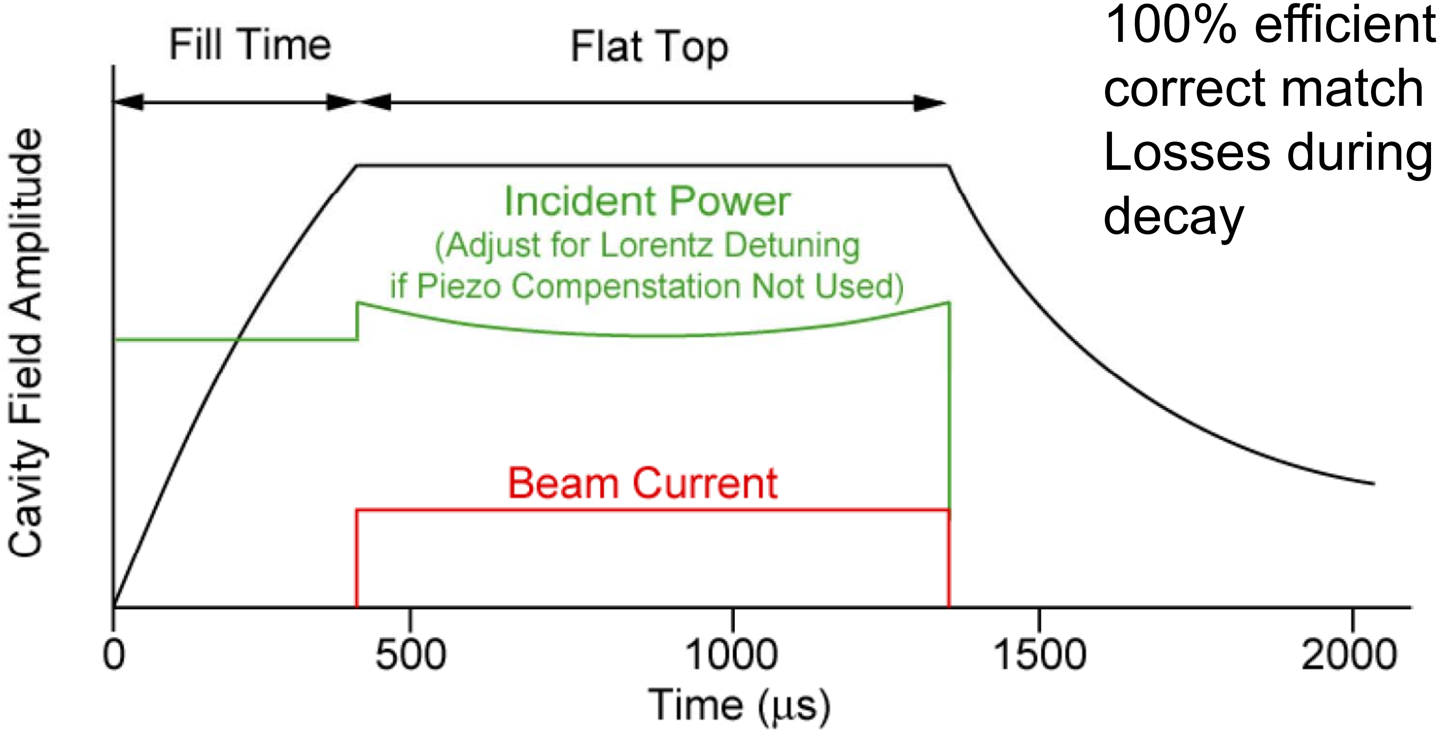


TABLE 4.3-1
Estimated Nominal Power Loads (MW) for 500 GeV Centre-of-Mass Operation

AREA SYSTEM	RF	CONV	NC MAGNETS	WATER SYSTEMS	CRYO	EMER	TOTAL (by area)
SOURCES e-	1.05	1.19	0.57	1.27	0.46	0.06	4.59
SOURCES e+	4.11	7.32	6.52	1.27	0.46	0.21	19.89
DR	14.0	1.71	6.78	0.66	1.76	0.23	25.15
RTML	7.14	3.78	2.84	1.34	0.0	0.15	15.24
MAIN LINAC	75.72	13.54	1.41	9.86	33.0	0.4	134.84
BDS	0.0	1.11	18.48	3.51	0.33	0.20	23.63
DUMPS	0.0	3.83	0.0	0.0	0.0	0.12	3.95
TOTAL (by system)	102.0	32.5	36.6	17.9	36.9	1.4	227.3

RF Fill Dynamics

- Adjust Qext to match cavity impedance (R/Qo * Qext) to the beam impedance (Gradient / Current) so zero reflected power during fill.
- For ILC, Qext = 3.5e6 so cavity BW = 370 Hz (ΔL ~ 1 micron).
- Need to achieve ~ 0.1% energy gain uniformity with LLRF system
  - Feedback will maintain constant ‘sum of fields’ in 26 cavities



100% efficient with correct match
Losses during fill & decay

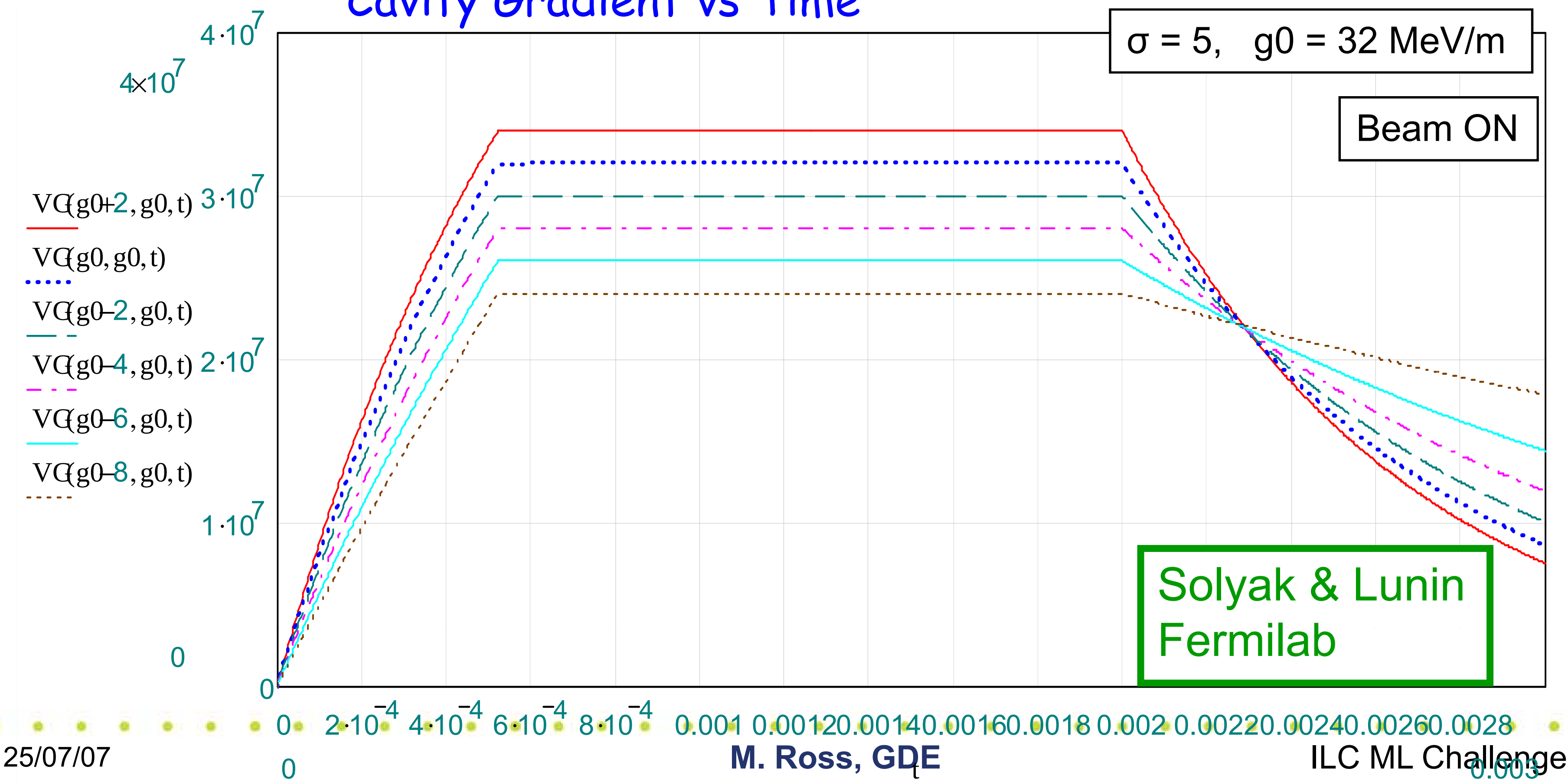
Cavity limitations differ:

- (different from LHC and TeV where the weakest magnet can limit entire machine performance)
- But cavities are fed from a single source
  - Tailoring input coupling and power can offset this but:
  - this requires power and
  - may prove difficult if we insist on flexible operation
- Take a model RF unit made from cavities like those recently produced at DESY…

Cavity Operation – Beam ON

- There are 2 controllable elements:
  1. **the klystron power (common to 24); tap fraction for each cavity**
  2. **The rate at which power feeds into each cavity (coupler – Q_ext)**
- There are 2 fundamental goals:
  1. **Flat gradient as a function of time during the pulse for each ↓**
  2. **Maximum 'practical' field in each cavity**
- Final: minimize wasted power; provide variability as needed for flexible ops

Cavity Gradient vs Time



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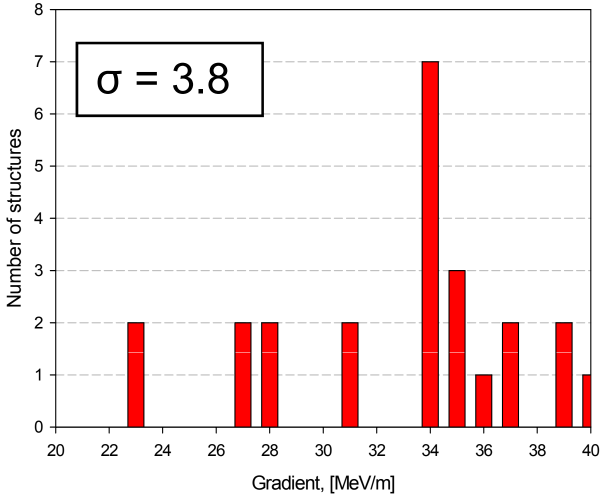
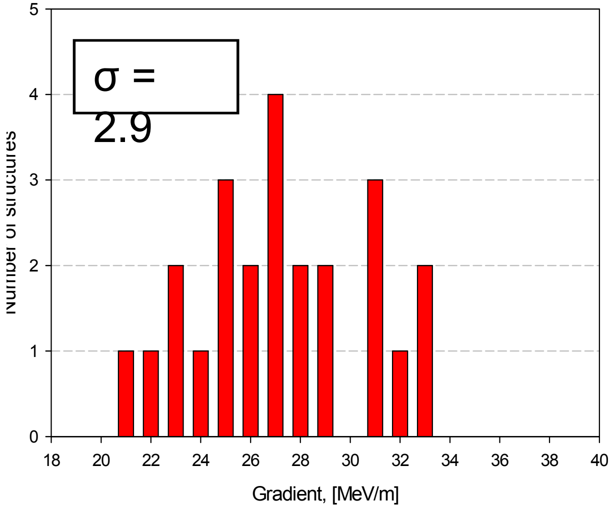
Cavity Gradient Distribution Approximation

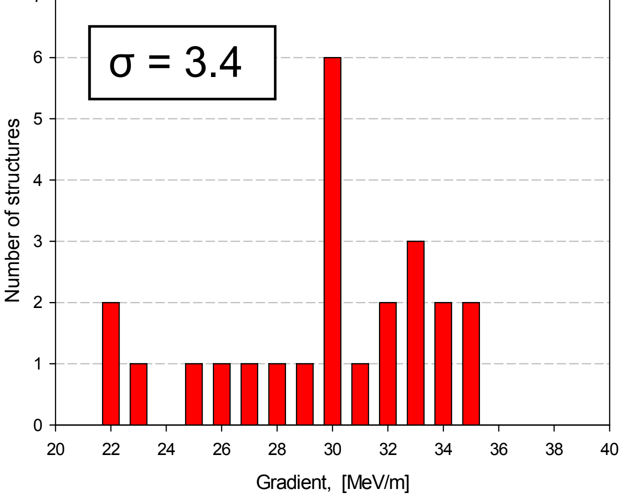
- 3rd Production EP all (Q0 = 10^10)



4th Production EP (Q0 = 10^10)



Modules ACC(5,6,7)*
Beam:ON



* R. Lange (*DESY)*, *TTC Meeting*, FNAL, April 2007

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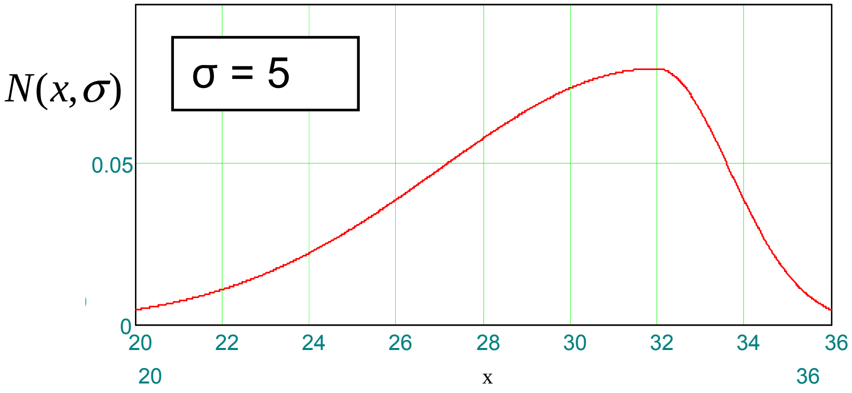
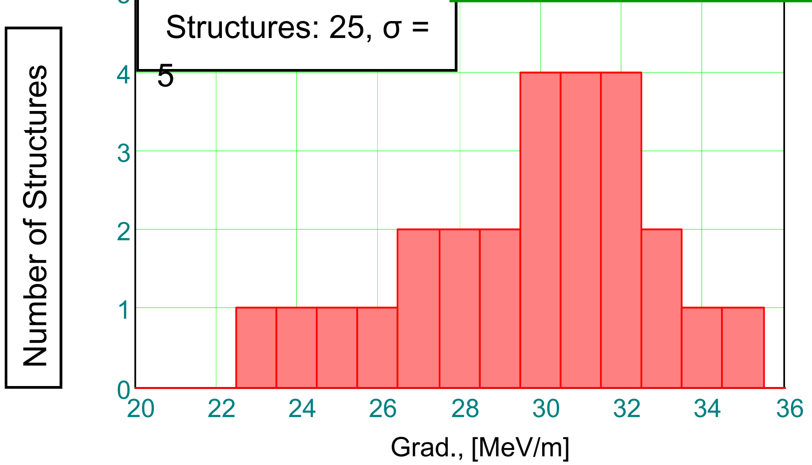
Asymmetric Gaussian Distribution:

$$N(x,\sigma) = \begin{matrix} G(x,\sigma), x < g0 \\ G(x,\sigma/3), x > g0 \end{matrix}$$





Cavity Operation, Beam ON

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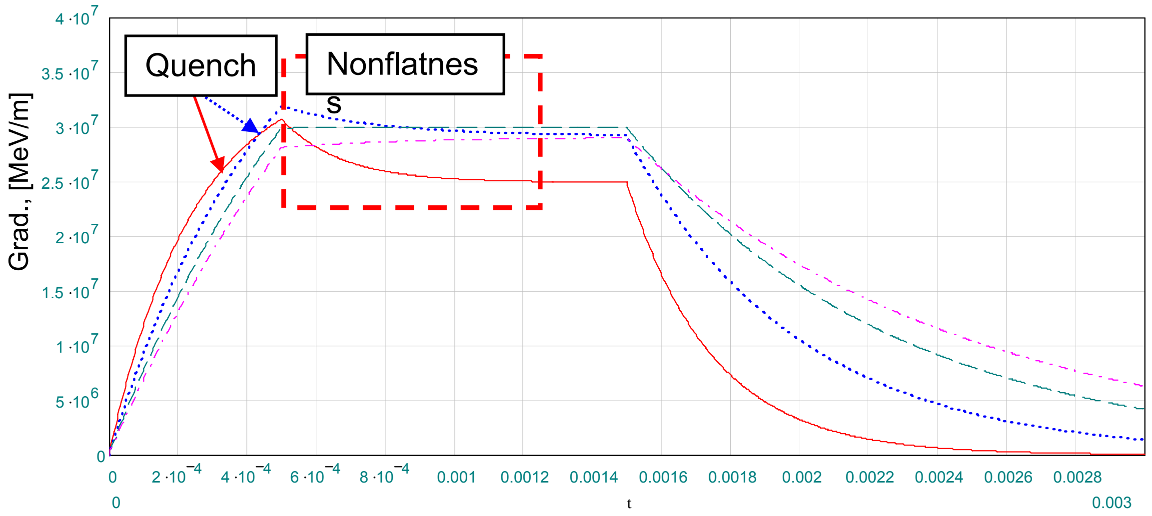
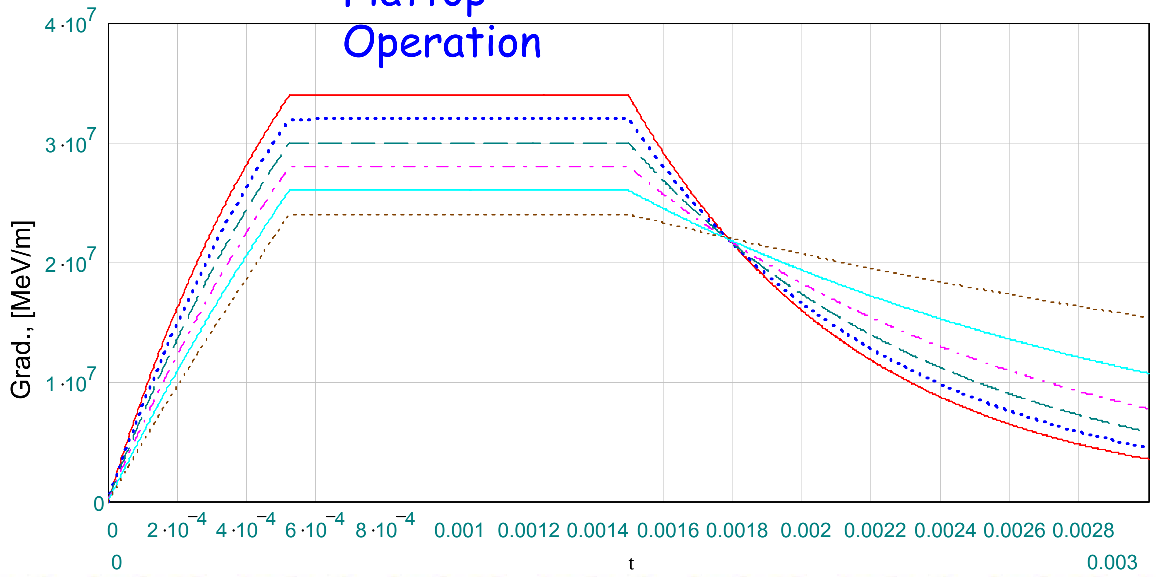
Cavity Gradient vs Time



If we will tune Q_i of each cavity to actual gradient $<G_i>$ then it will cause either quench or nonflatness . The reason is that each cavity has an individual filling time while a beam is coming to all cavities simultaneously.

Flattop Operation



It is possible to restore flat top operation by tuning each cavity both Q-factor and Input Power (Q_i and P_i)*:

$$Q_i = \frac{Q_0 * \ln(2)}{\ln\left(1+\frac{G_i}{<G_0>}\frac{Q_0}{Q_i}\right)}$$

$$P_i = \frac{1}{4}P_0\left(1+\frac{G_i}{<G_0>}\frac{Q_0}{Q_i}\right)^2\frac{Q_i}{Q_0}$$

* Index “0” correspons to matched gradient $<G_0>$ (no power reflection).

Cavity Gradient Distribution, Beam ON

Input RF Power (PK) vs Structure Gradient

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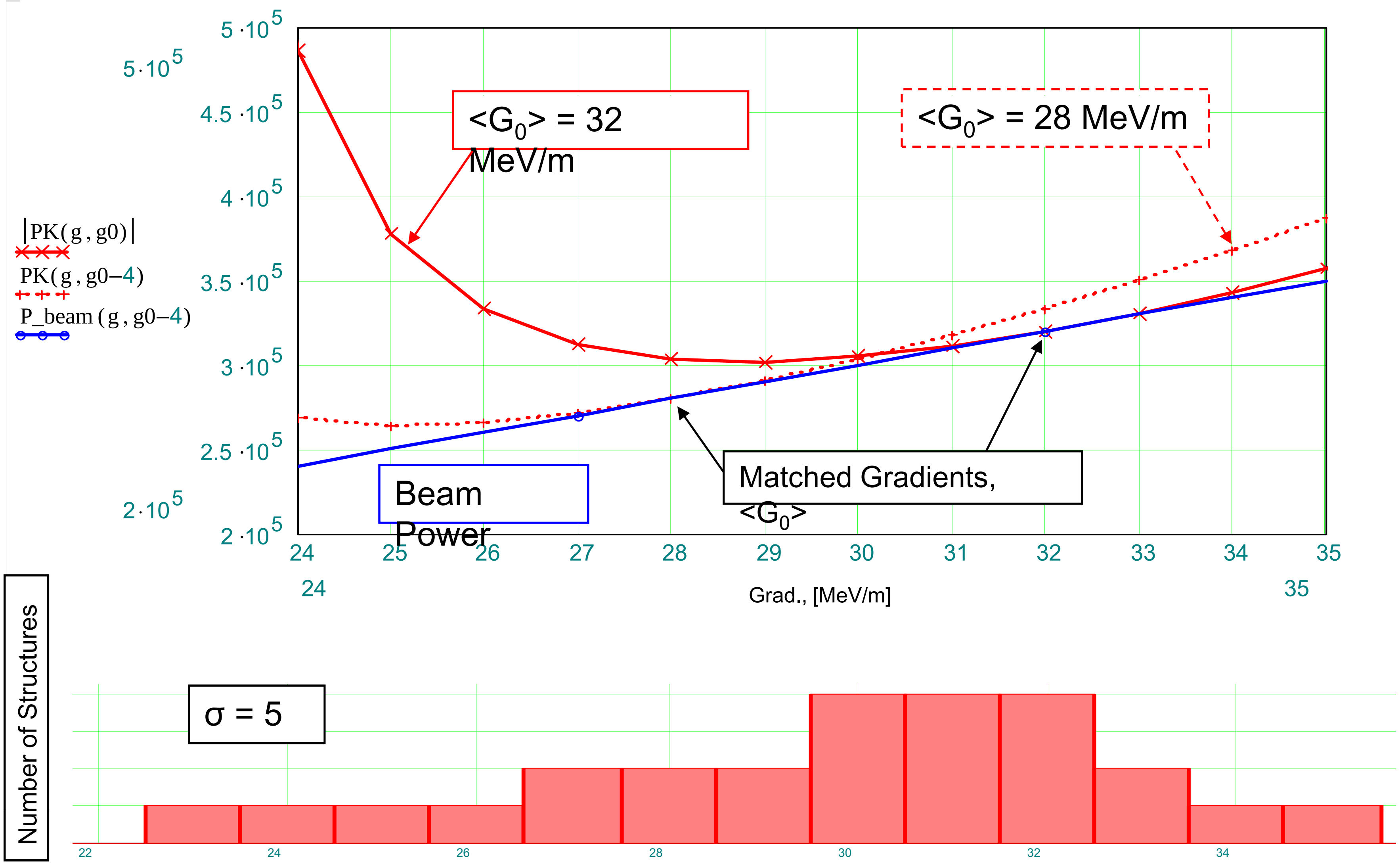

Cavity Operation, Beam ON

Total Power Loss vs. Tuning Structure Gradient <G>

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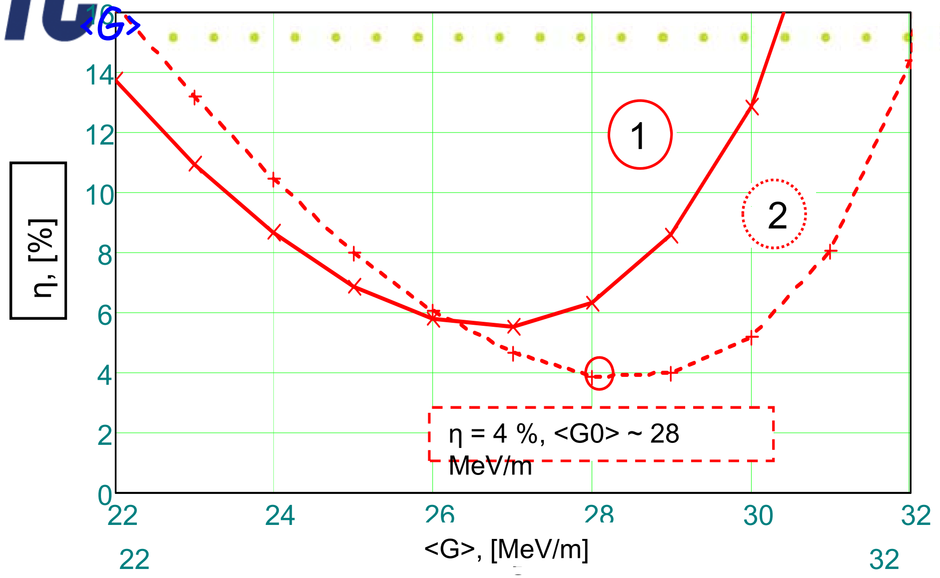
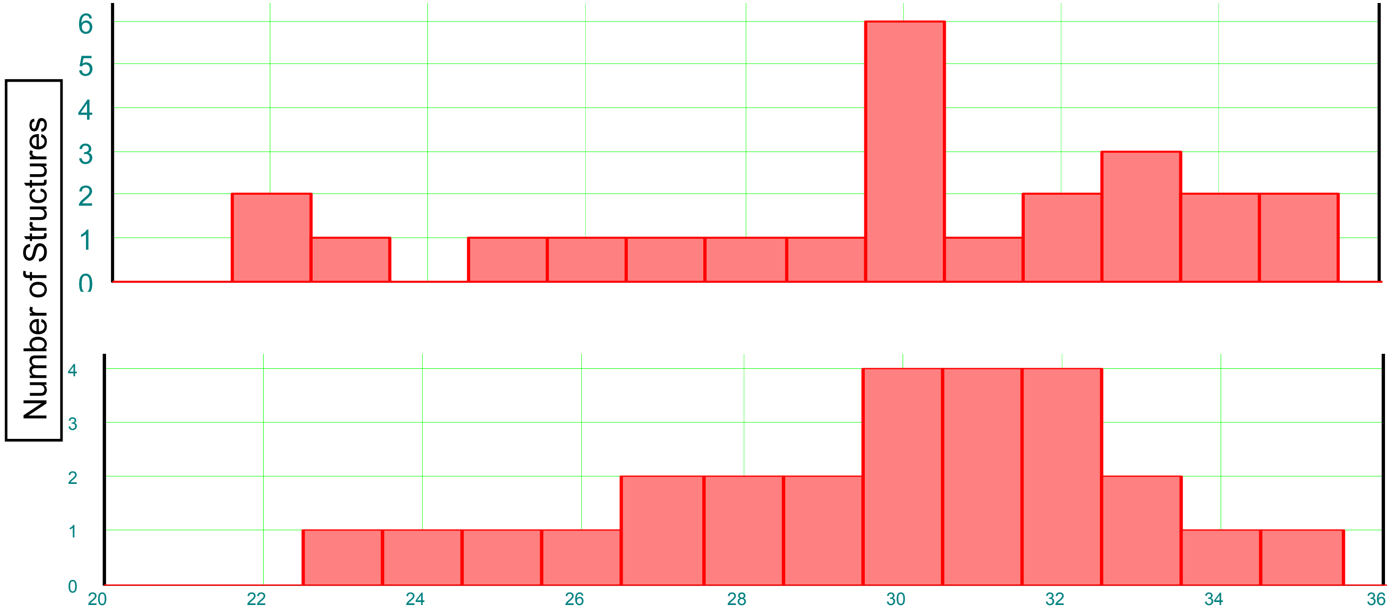


η = 4 %, <G0> ~ 28 MeV/m

$$\eta = \frac{\sum P_{reflected}}{P_{klystron}} * 100\%$$



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Real Gradient Distribution
(Modules ACC(5,6,7) Beam:ON)

2

Expected Average Asymmetric Gaussian Gradient Distribution

Multiple Cavity Operation

- There is an optimum in a total power efficiency vs. matched gradient
- Expected additional average power is about 4 % at optimum gradient
- We can further lower the power loss and simplify RF distribution system by sorting cavities in pairs with nearly equal gradients
- We must also consider cavity over-voltage

Controls:

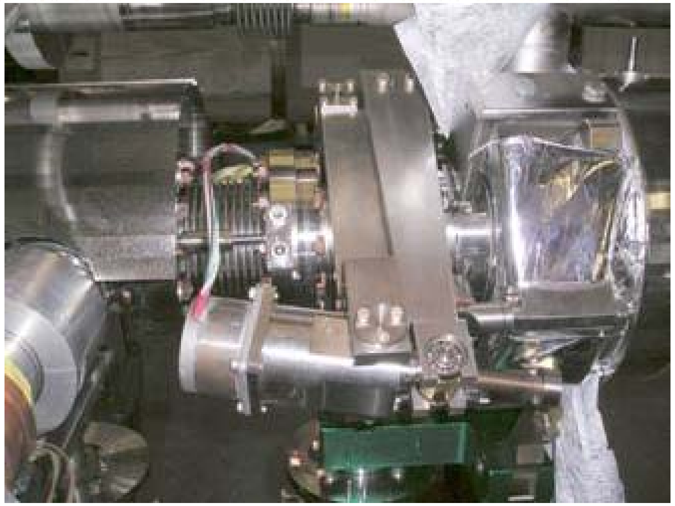
- achieving the perfect RF match to a each cavity
- Static
  - **Accounting for cavity variations**
  - **Feedforward compensation of cavity detuning due to Lorentz force**
- Dynamic - Stabilization of
  - **Microphonics**
  - **Beam intensity fluctuations**
  - **Thermal**
  - **Transients**
- Challenge of operating near the gradient limit

Controls Example: Fast Tuner

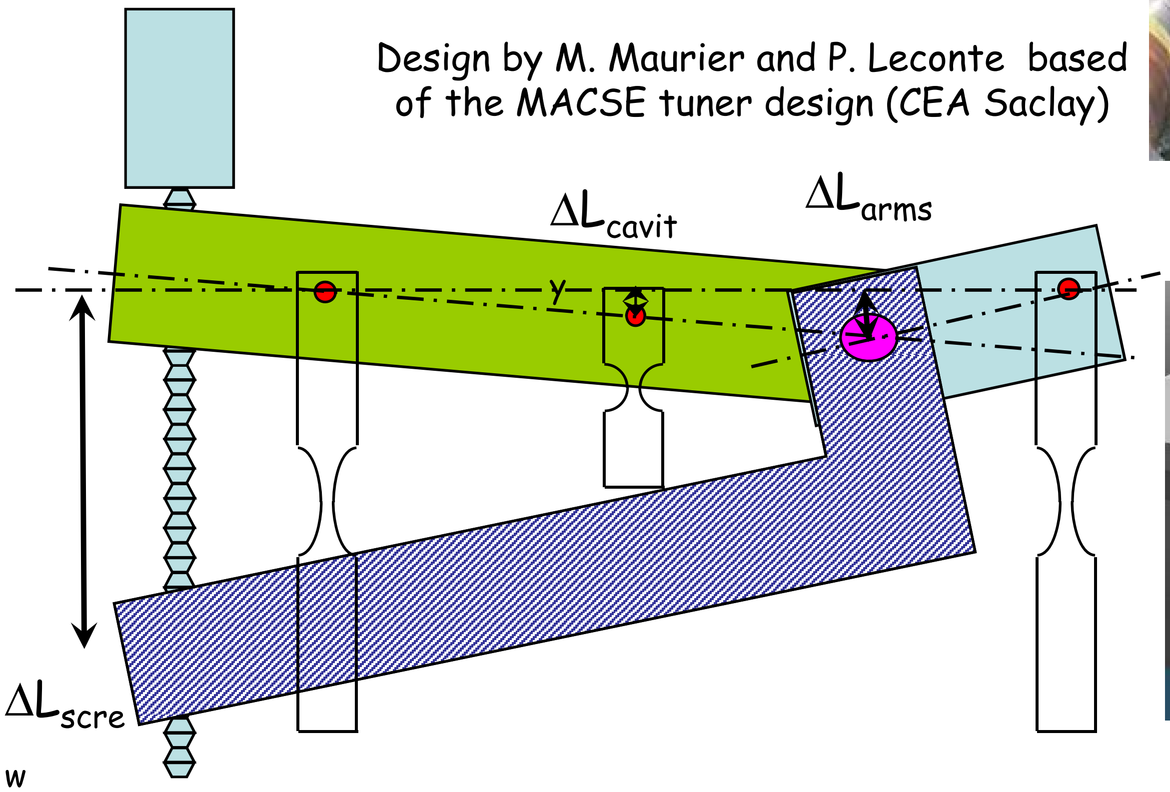
- Apply small axial squeeze to compensate for Lorentz force distortion
- Initial demonstration for each cavity
  - **Measure detuning**
  - **Compensate detuning individually, one after the other**
  - **In addition**
    - Work on piezo diagnostics: Impedance measurement
    - Measure transfer functions from one piezo to another
      - Is there any crosstalk between the cavities?
- Demonstrate compensation on full module for all cavities simultaneously
  - **With RF feedback**

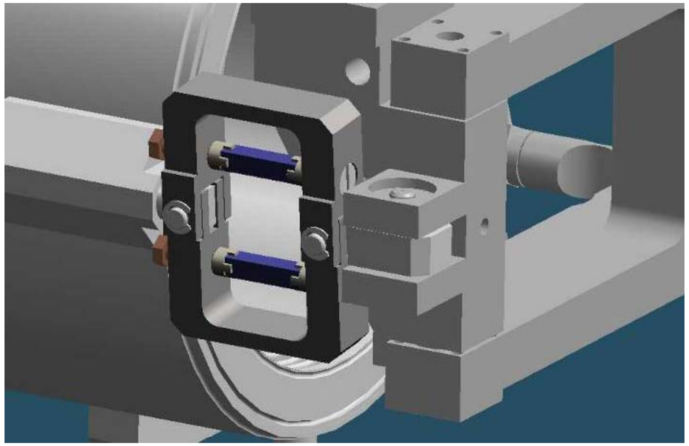
Tuner Setup

- Current design in use at FLASH
  - **Design by CEA – Saclay**
- Lever-based mechanism



Design by M. Maurier and P. Leconte based of the MACSE tuner design (CEA Saclay)





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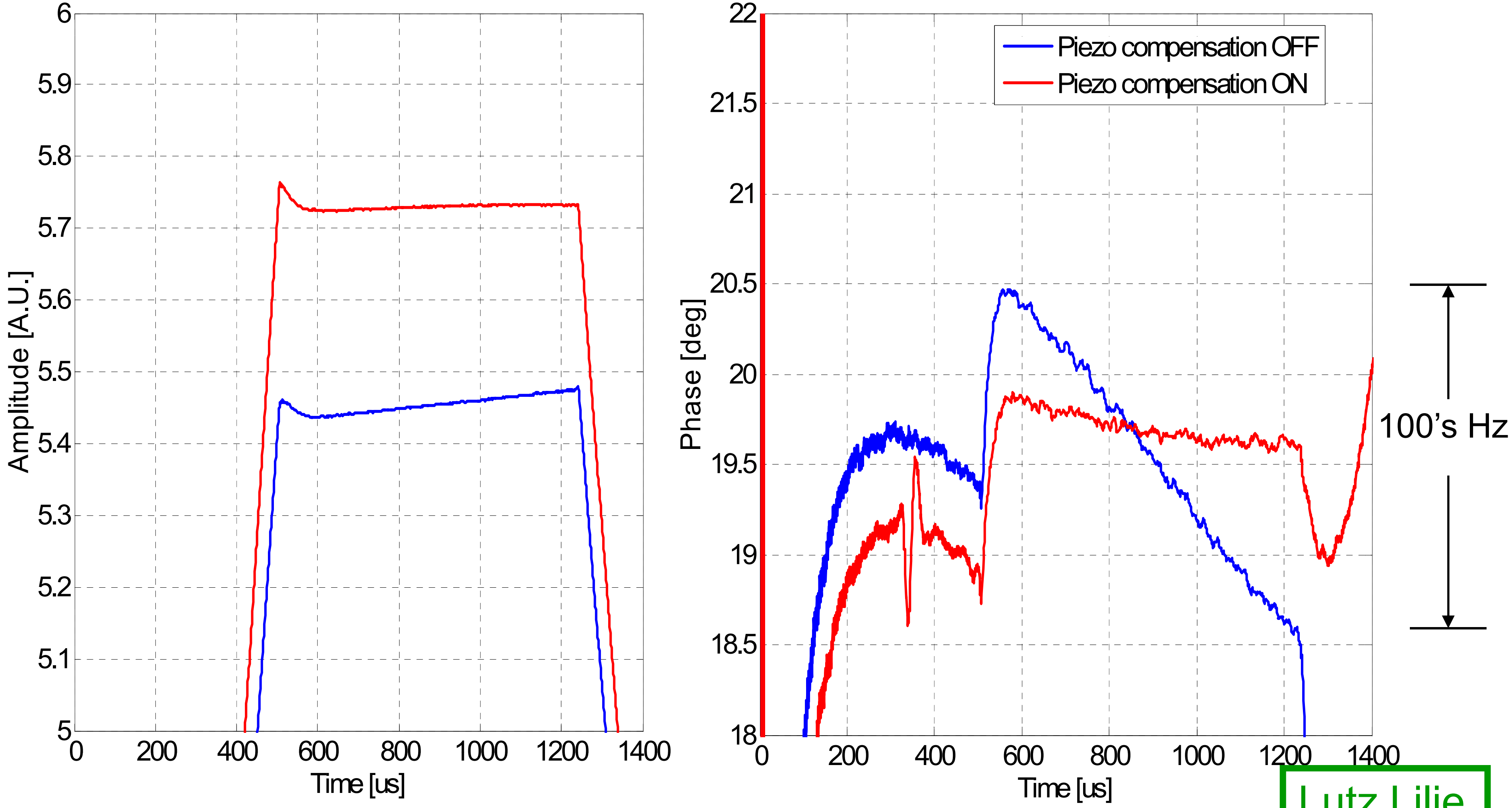
Operation of Full module – Vector-Sum



Vector Sum of Module 6 with and without piezo active compensation
RF feedback ON, same control-loop-gain setting

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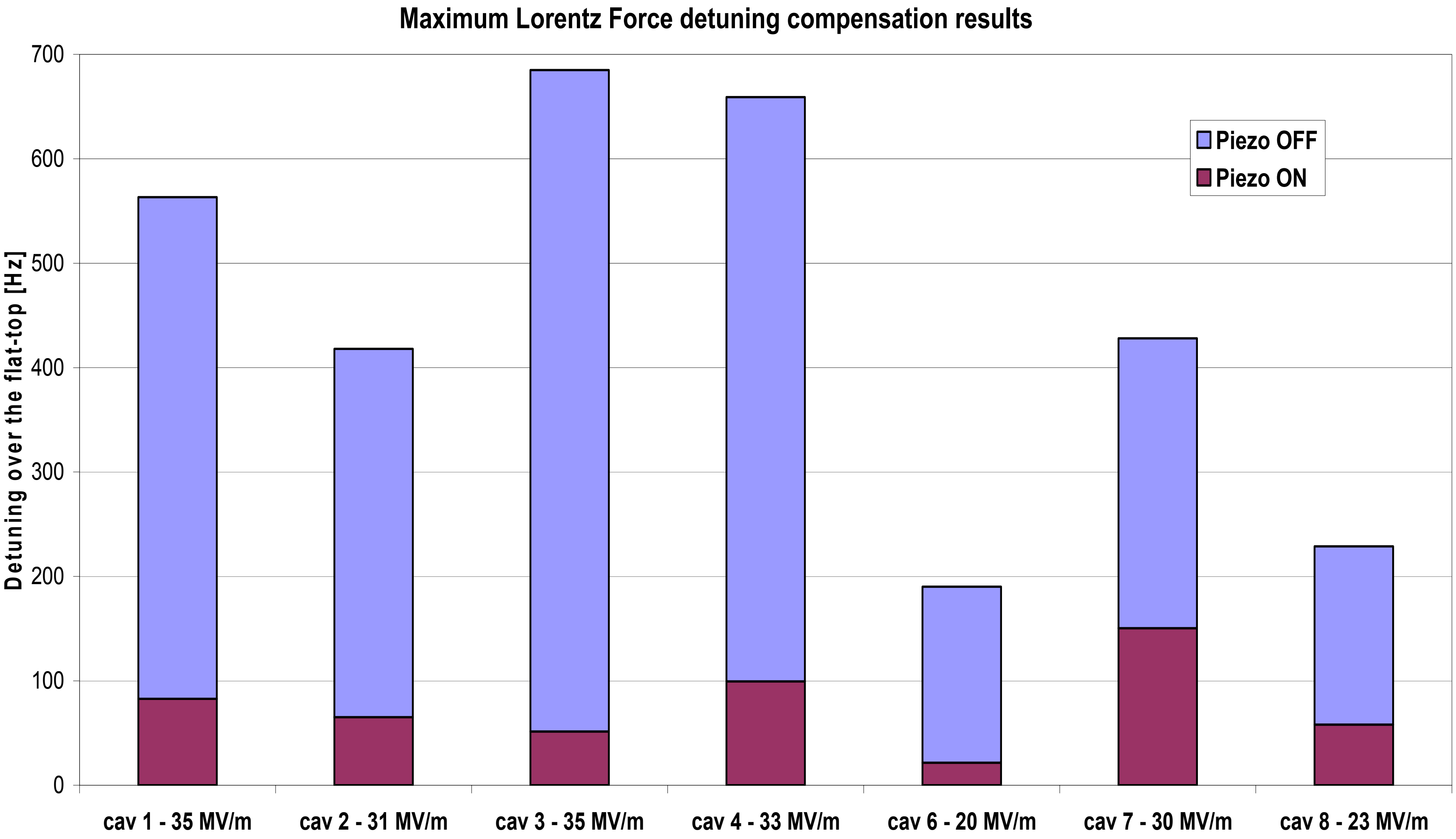
Compensated Detuning per Cavity



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SCRF Linac Beam Dynamics

- Chromatic effects:
  - **Cavity misalignment**
  - **Dispersion**
  - **Coupling (x y)**
- Collective –current based- effects:
  - **Single bunch**
    - Wakefields – interaction with the structure/surrounding hardware
  - **Multi bunch**
    - Resonant excitation of higher order modes
- Coupler Kicks and Dark Current

Resonant excitation of higher order modes

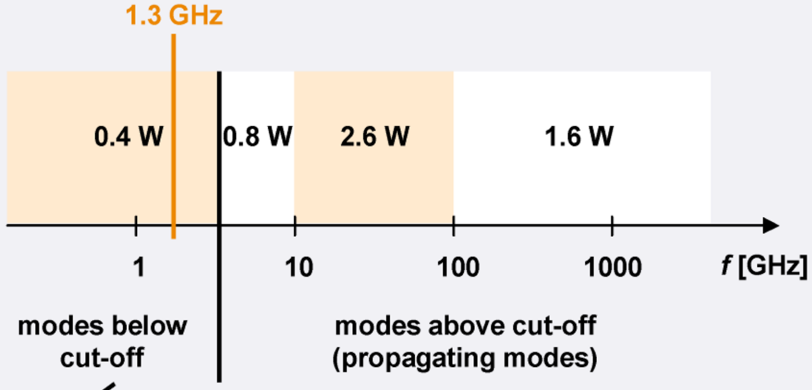
- We power the cavity with a strong single frequency –
  - **Each beam bunch is a 'delta function' that has a broad frequency spectrum that couples to the cavities natural resonant modes.**
    - Modes with phase velocity = *c* have the strongest coupling
  - **Each cavity will have slightly different spectra because of fabrication differences**
- Some modes have a long life time
  - **Trapped modes may exist**
  - **Near cut-off, modes may have large characteristic dimensions**
- The bunch train spectrum has a sequence of lines which may couple strongly to cavity / cryomodule modes

Damping of Higher Order Modes (HOMs)

The spectrum of the electron bunch ($\sigma_z = 25\ \mu m$) reaches high frequencies up to 5 THz.

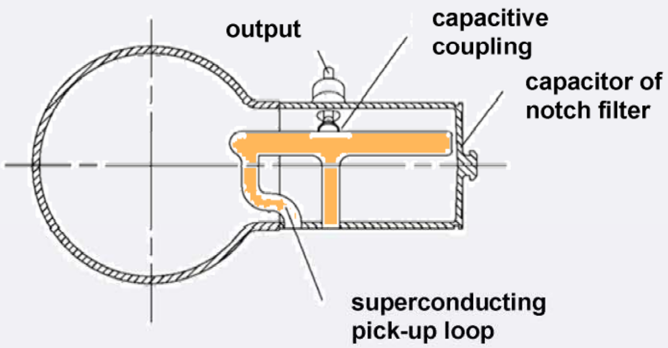
The standard accelerator module has an integrated loss factor of 135 V/pC.

The total power deposited by the nominal beam is 5.4 W per module.

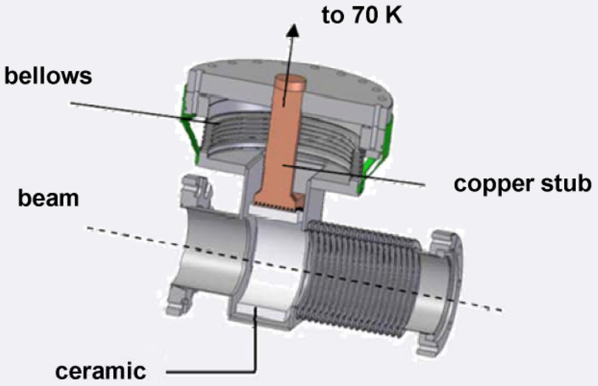


The design of the HOM coupler and the beam pipe absorber take into account a possible XFEL upgrade (more bunches / CW mode).

The HOM coupler was tested in CW mode. The absorber is specified for 100 W.

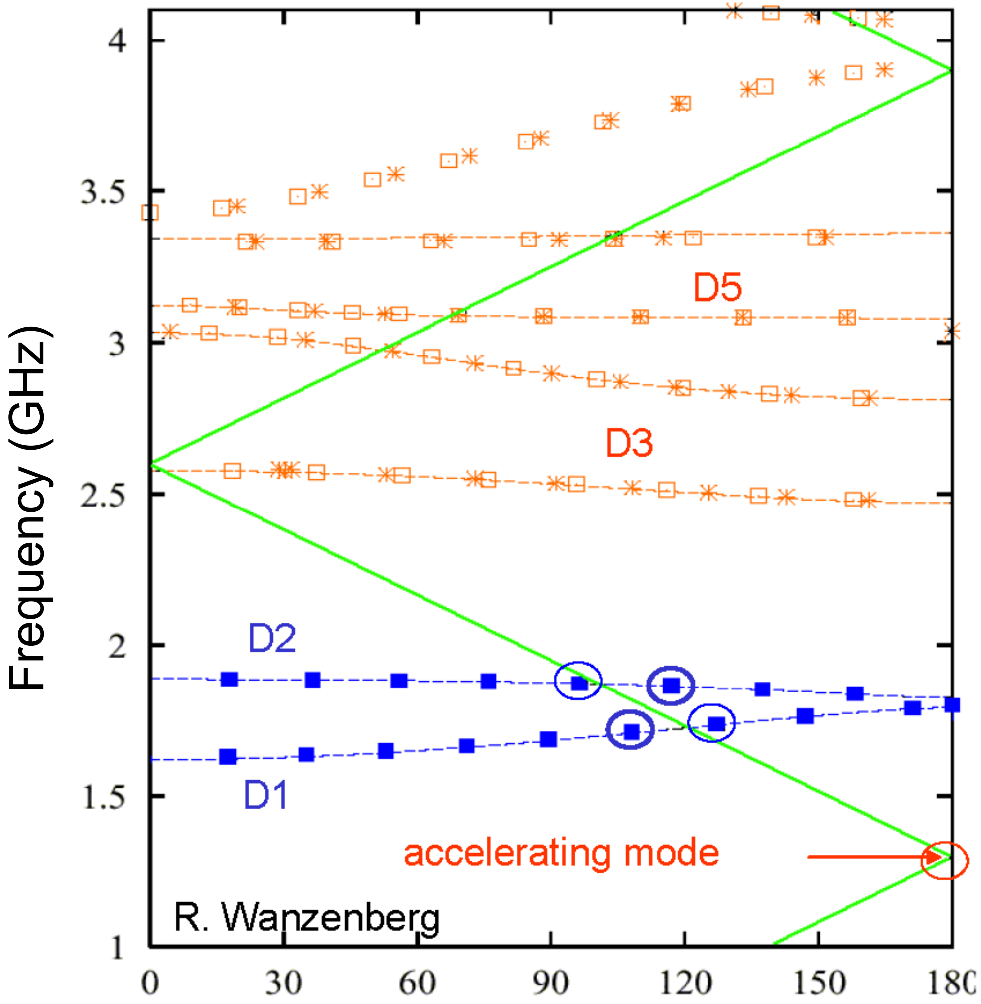


HOM coupler



beam pipe absorber

TTF 9-cell cavity HOMs

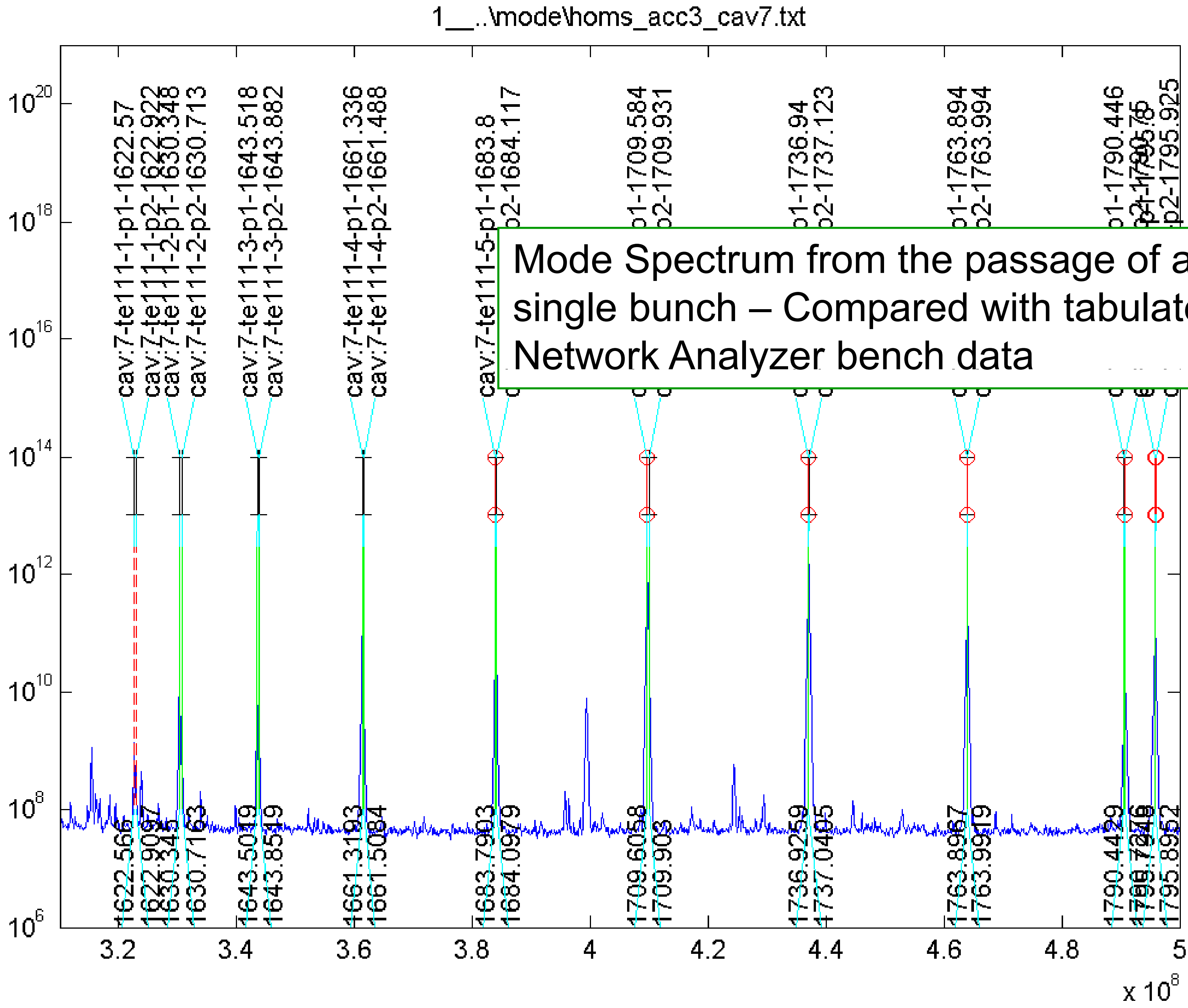


Modes Below cutoff

⇒ no propagation

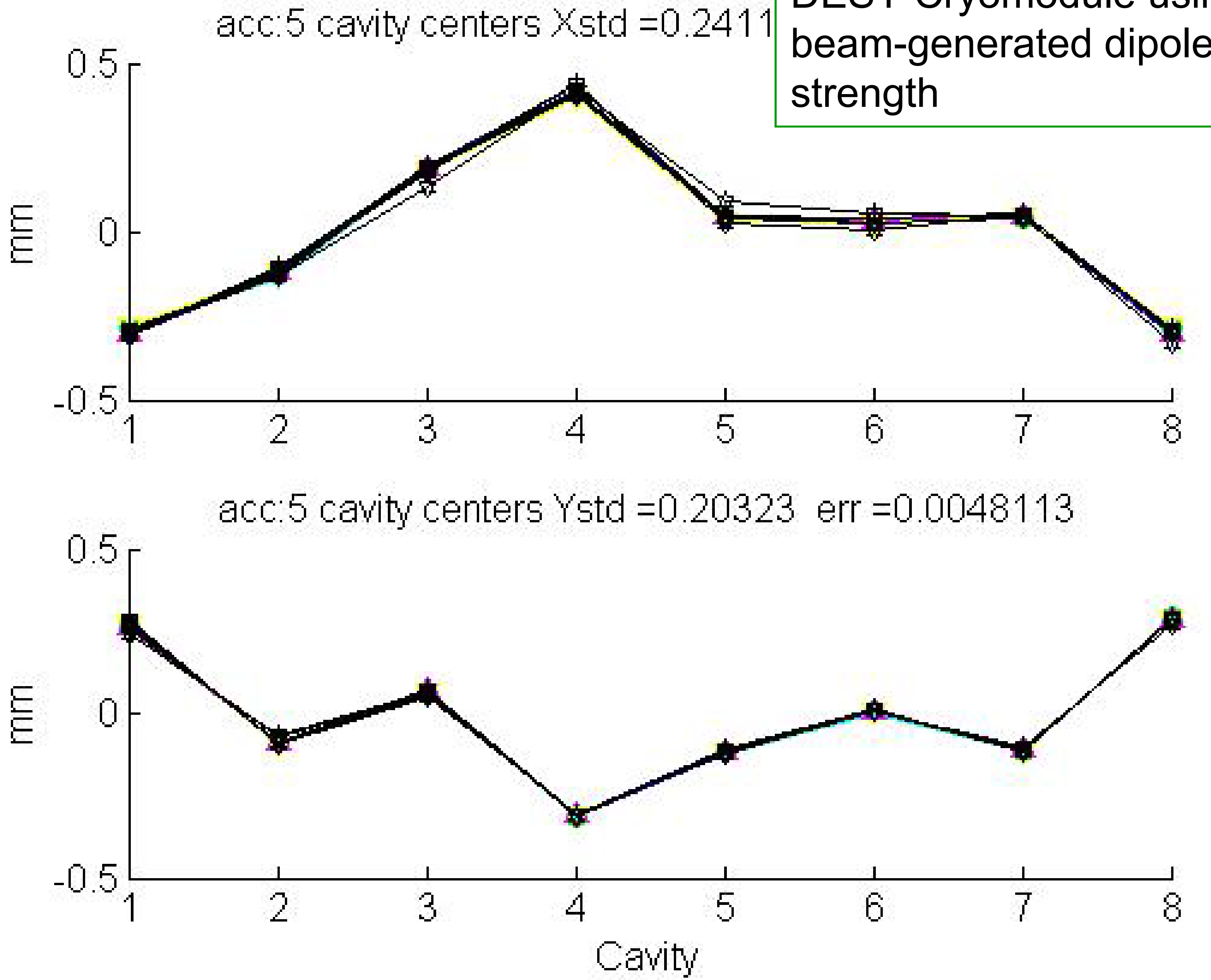
⇒ R/Q easy to compute
in one cavity.

	Frequency [GHz]	R/Q [Ω/cm2]
TE111_6	1.705	11.1
TE111_7	1.730	15.6
TM110_4	1.865	6.4
TM110_5	1.875	9.0



Mode Spectrum from the passage of a single bunch – Compared with tabulated Network Analyzer bench data

Relative Cavity centers in a DESY Cryomodule using beam-generated dipole mode strength



Beam Size and Divergence

E (GeV)	σ_x(μm)	σ_y(μm)
5	300	15
15	150	8
250	30	2

Small Beams
Microns ; microradians
GeV ; KeV

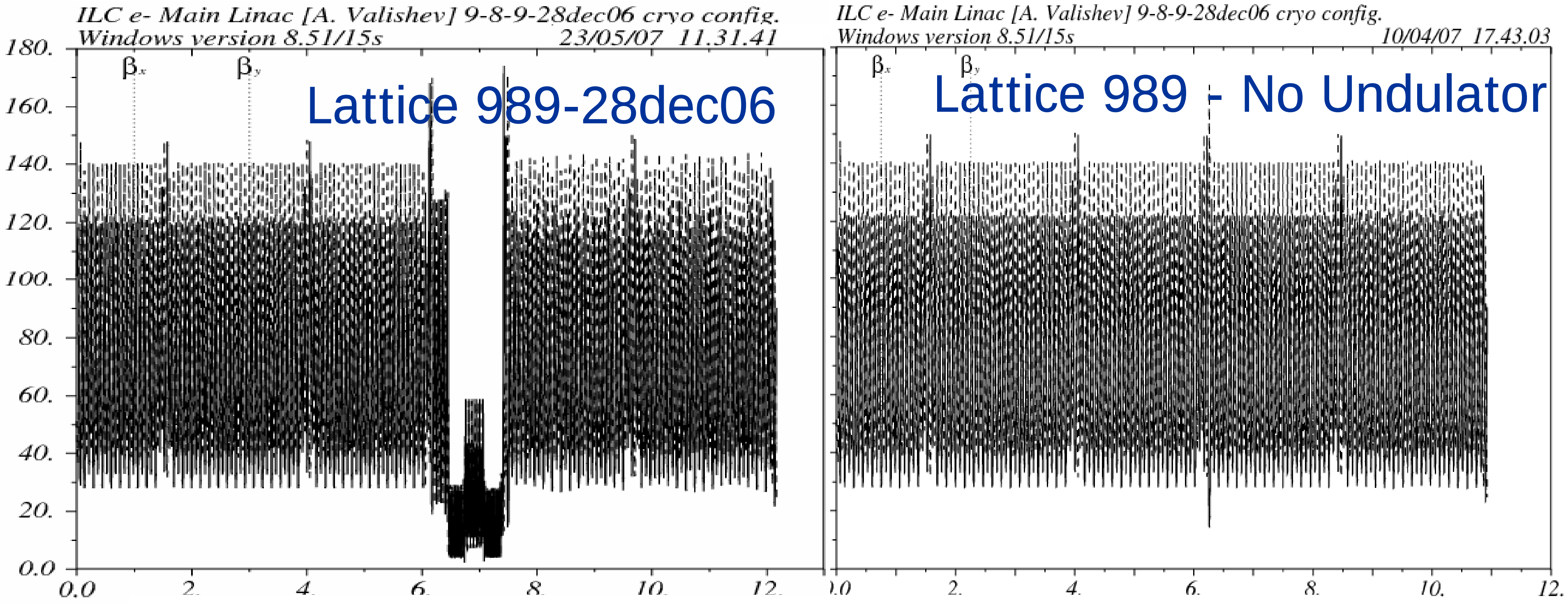
Simple minded:

Typical p⊥rms_y ~ 5KeV
Each cavity ~ 30 MeV
Cavity angular alignment tolerance ~ 300 μ rad
Cavity position tolerance ~ 300 μ m
Mechanical distortions / microwave transverse fields

Dispersion in a linac

- Misaligned quadrupoles and BPMs generate orbit distortions;
  - **Results in beam dispersion which significantly increases projected emittance**
  - **Dispersion is a linear correlation: *y←→E***
- Kicks are $n\sigma$_y ; δ ~1e-3
  - **Lattice is weak so 'filamentation':**
    - (difference in β phase advance within bunch)
  - **is small (ILC ML ~ 30*2π)**
  - **Thus the correlation can be 'subtracted out' using a trajectory bump**
- Beam – Based Alignment →
  - **find the dispersion-free trajectory**
  - **Algorithms, Simulations, Systematic Errors**

9-8-9 Lattice β-functions



Lattice 989-28dec06

Lattice 989 - No Undulator

Lattice Repository

- Acc. Division of Fermilab supports centralized lattice repository
  - **Controlled write access; Revision history**
- ILC ML lattices (read only) have been placed into the repository https://lattices.fnal.gov/

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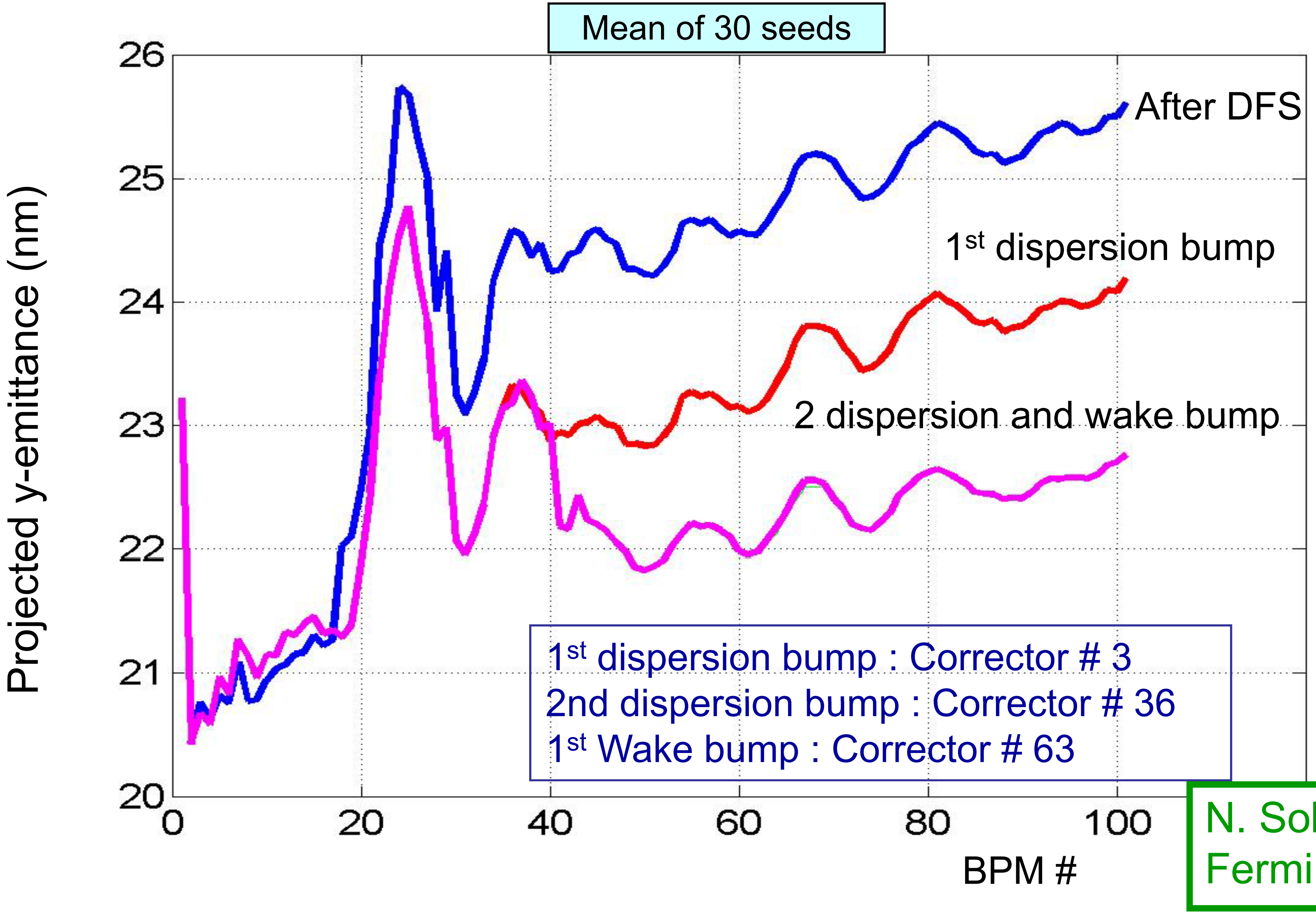
Effect of Bumps for Static Tuning



1st dispersion bump : Corrector # 3
2nd dispersion bump : Corrector # 36
1st Wake bump : Corrector # 63

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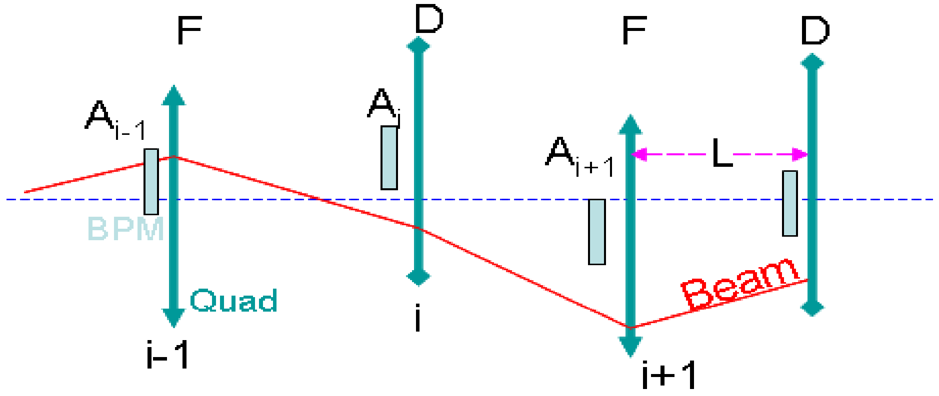
Beam –Based Alignment & Beam Stability and Steering

- (300x more precise…- than a-priori mechanical placement)
- Start with these:
  1. **Dispersion-free steering**
  2. **Quadrupole shunting**
  3. **Ballistic alignment**
  4. **Kick minimization**
- Then try to keep it as things ‘drift away’
  – **Kind of feedback compensation for ground motion**

Adaptive Alignment (AA)– Basic Principle

Proposed by Vladimir Balakin in 1991 for VLEPP project



“local” method: *BPM readings (A_i)* of only 3 (or more) neighboring quads are used to determine the shifting of the central quad (Δy_i).

$$\Delta y_i = conv * [A_{i+1} + A_{i-1} - A_i * \{2 + K_i.L.(1 - \frac{\Delta E}{2E})\}]$$

conv : Speed of convergence of algorithm
A_i : BPM reading of the central quad and so on
K_i : Inverse of quad focusing length
L : Distance between successive quads (assuming same distance b/w quads)
ΔE : Energy gain between successive quads
E : Beam Energy at central quad

New position of quad & BPM:

$$y_i = y_i - \Delta y_i$$

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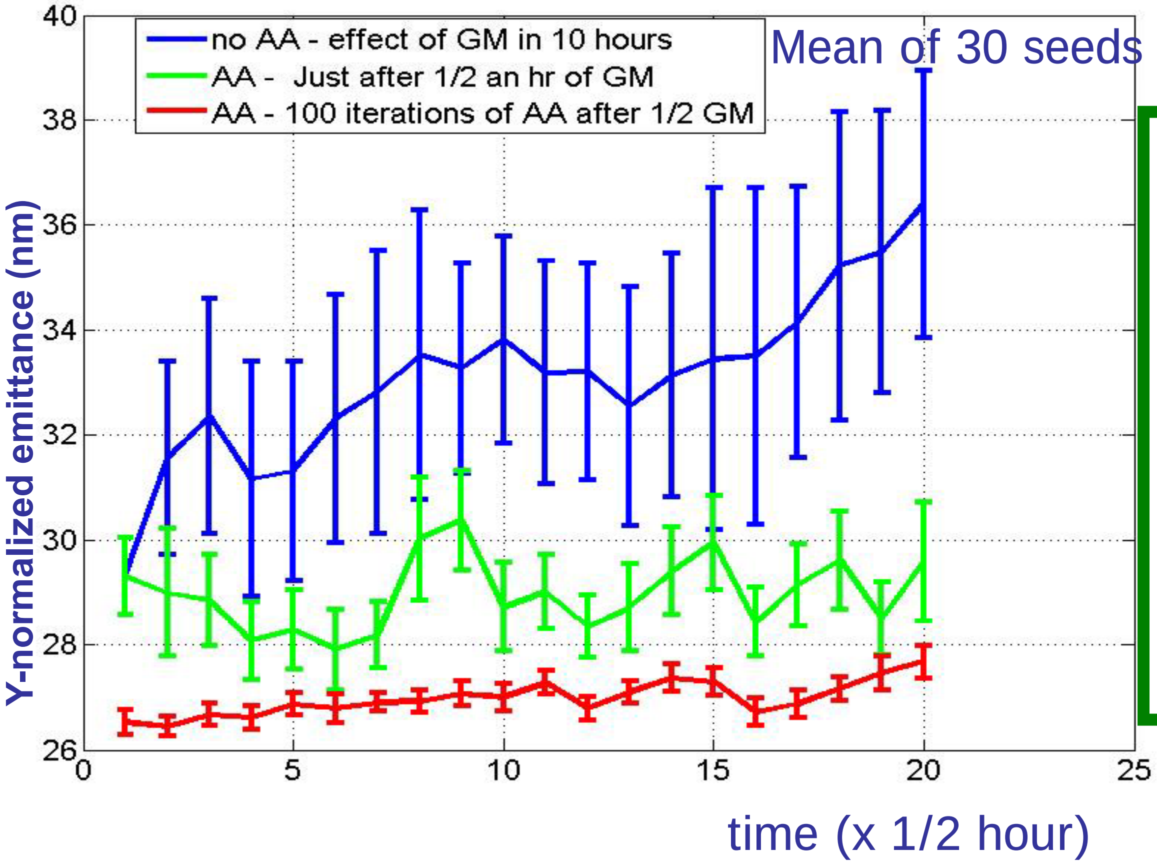
The procedure is iteratively repeated

Effect of Ground Motion

- AA of 100 iterations after every 1/2 hr. (conv. = 0.2)
- 30 different GM seeds (Model C)

Y-emittance (nm) @ Linac exit vs. time (1/2hrs.)



In half an hour of GM, emittance dilution increases by as much as ~ 5 nm b/w the subsequent AA iterations, which implies that AA will have to be done at this order or better!

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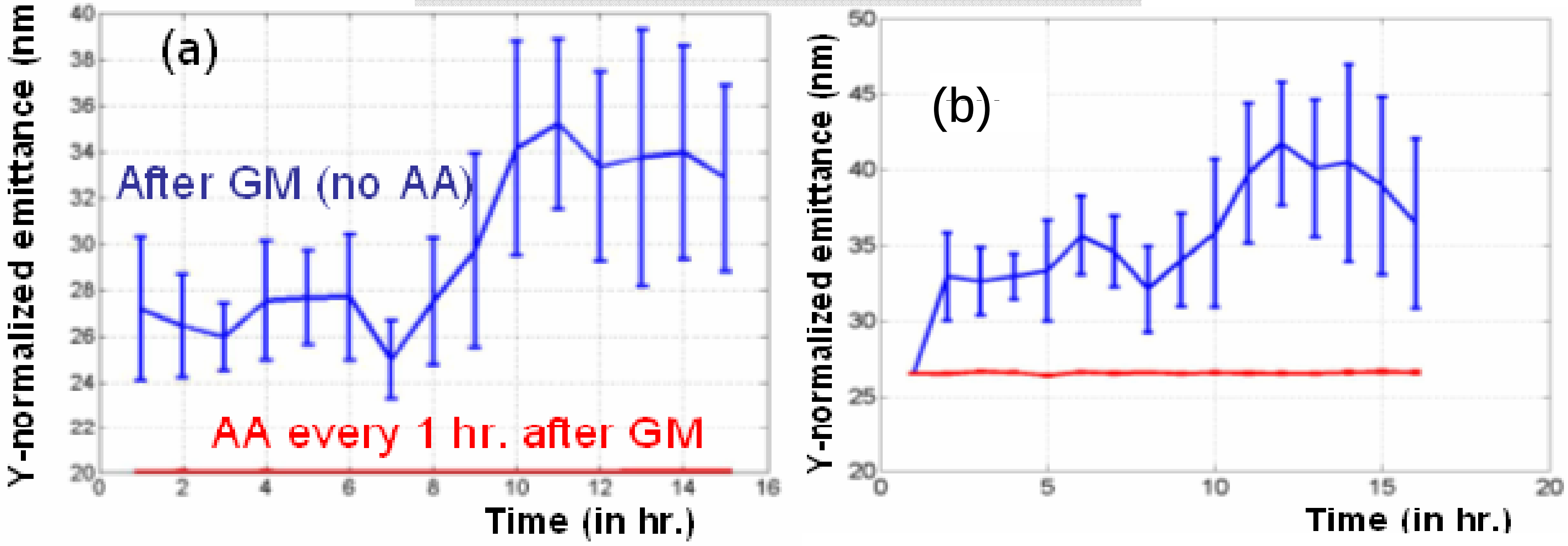
40 nm is nominal at IP;
DR output 20 nm

AA in perfect and DFS lattice

Average of 10 Ground Motion seeds



Normalized vertical projected emittance vs. time in

(a) Perfectly aligned Linac (b) Dispersion-free steered linac.

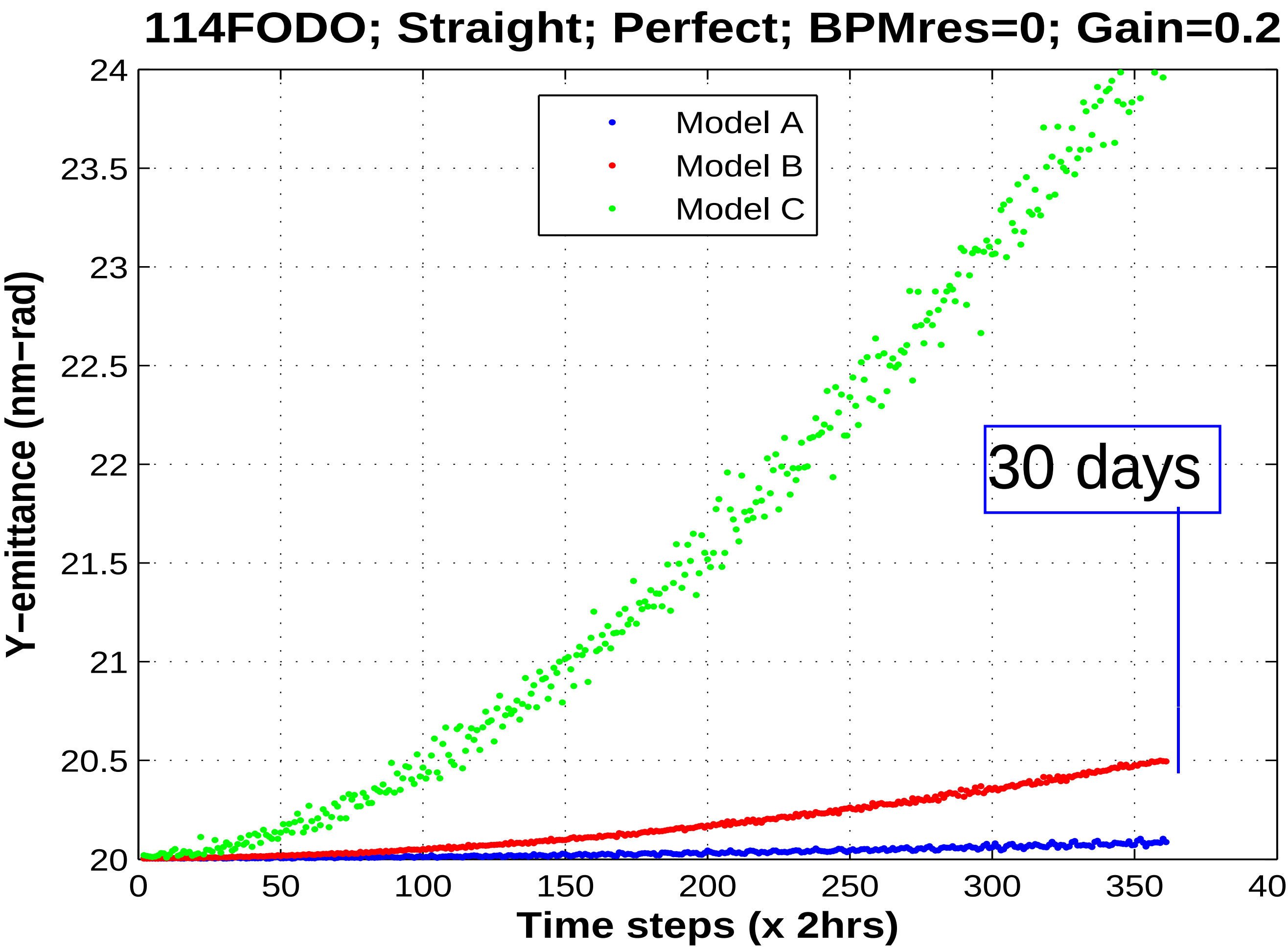
AA is implemented after every hour of GM model ‘C’ (noisy)

- » AA keeps the emittance growth even for model C under control
- » If orbit after DFS is used as a reference, then AA is not sensitive to BMP-to-Quad offsets

N. Solyak,
Fermilab

Effect of GM models

Y-emittance (nm) @ Linac exit after 100 AA iterations for different GM models 'A', 'B' and 'C'. Total period - one month, time step - 2 hours

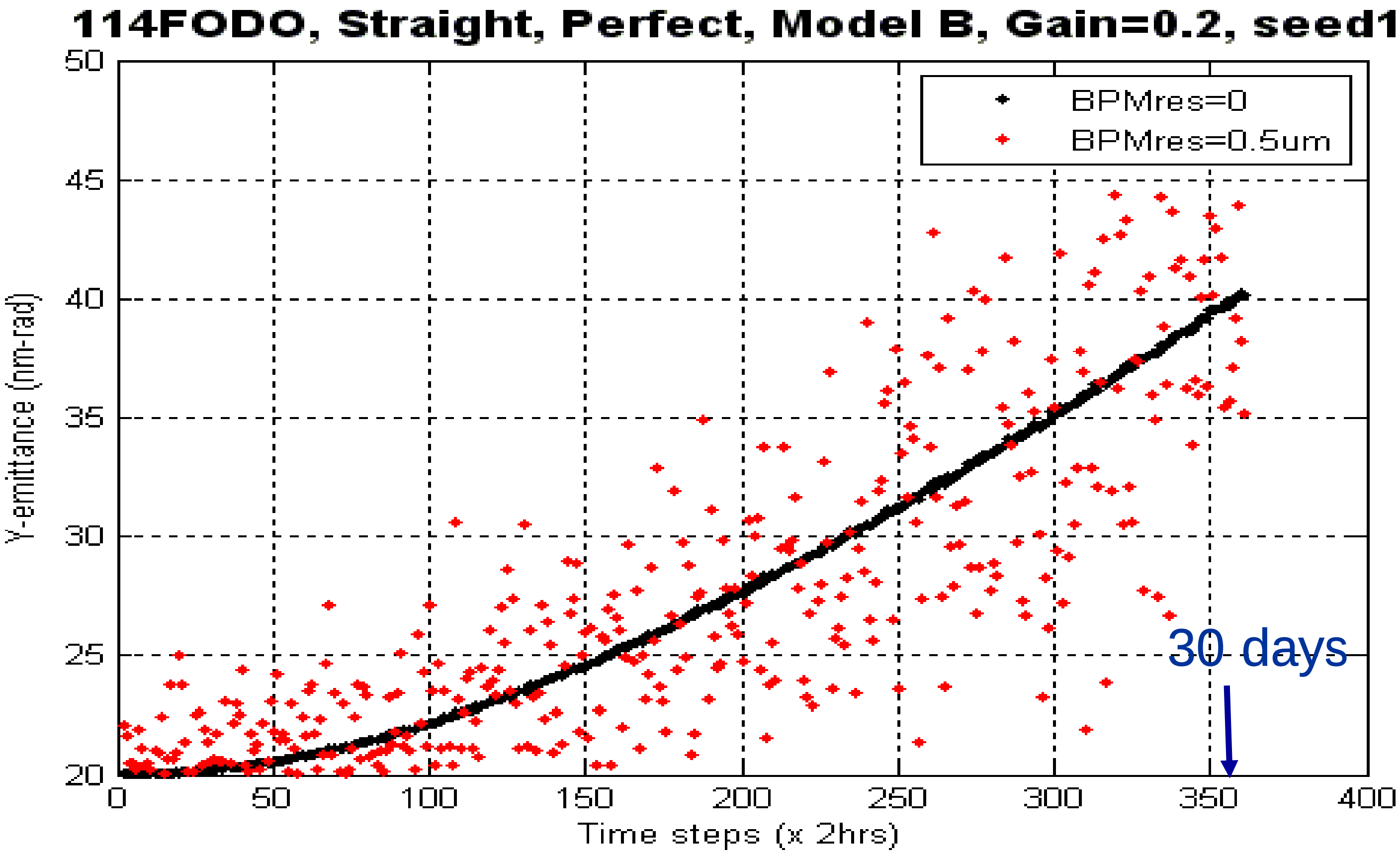


Average of 10 GM seeds for each GM model

Convergence= 0.2

N. Solyak, Fermilab

Effect of BPM resolution



N. Solyak, Fermilab

The effect of BPM resolution for AA correction can be significantly reduced by averaging information from all bunches in one train or even by using information from a number of previous pulses. This was confirmed in simulations done for short lattice.

Can we build it better?

- Can it be better tuned?
- Can we afford the emittance degradation?
- Reducing iris size increases wakefield
  - **But increases accelerating gradient by**
  - **76 → 60mm (20% reduction in diameter) decreases surface magnetic field to allow ~42 MeV/m accelerating gradient**
  - **In the scaled elliptical TESLA shape**
  - **(a gain similar to ICHIRO – KEK)**
  - **(christened 'Yao Ming' by SLAC's Zenghai Li)**

Cold mass alignment strategy

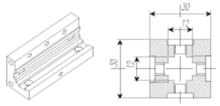
- The Helium Gas Return Pipe (HeGRP) is the system backbone
- The 3 Taylor-Hobson spheres are aligned wrt the HeGRP axis, as defined by the machined interconnecting edge flanges
- Cavities are individually aligned wrt the aligned T-H spheres
- Cavity (and Quad) sliding planes are parallel to the HeGRP axis by machining (milling machine)
- Longitudinal cavity movement is not affecting alignment
- By design the differential thermal contractions preserve parallelism
- Variation of axis distances by differential contraction are fully predictable and taken into account
- Sliding supports and invar rod preserve the alignment while disconnecting the cavities from the huge SS HeGRP contraction
  - 36 mm over the 12 m module length cooling from 300 K to 2 K

WPMs to qualify alignment strategy

WPM = Wire Position Monitor

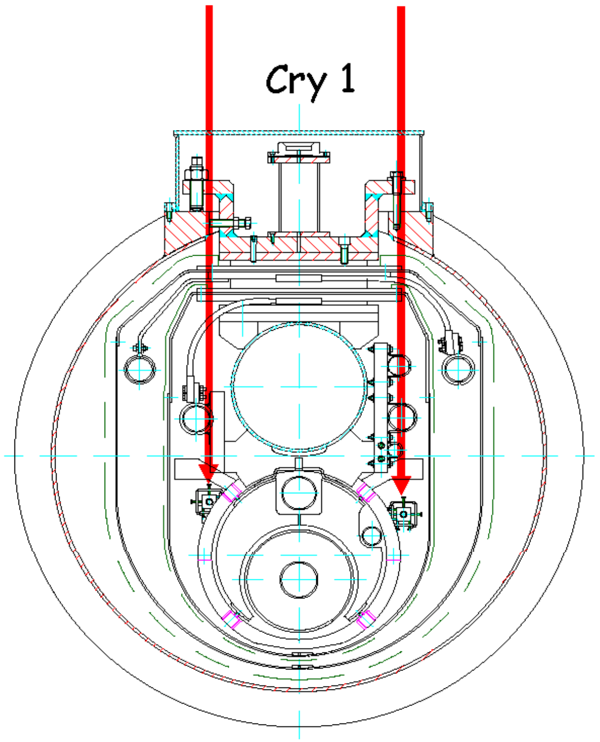
On line monitoring of cold mass movements during cool-down, warm-up and operation

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

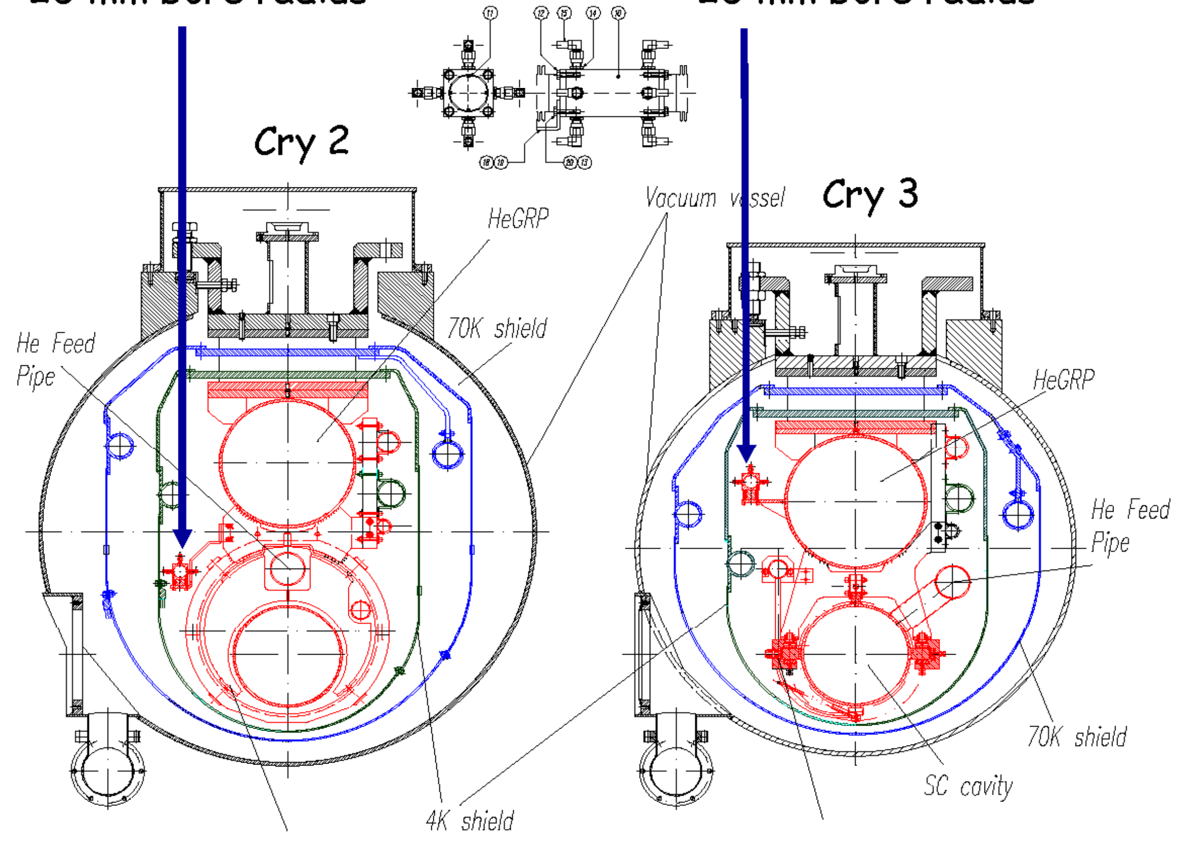


1 WPM lines
1 sensors per active element
25 mm bore radius

1 WPM line
7 sensors/module
25 mm bore radius



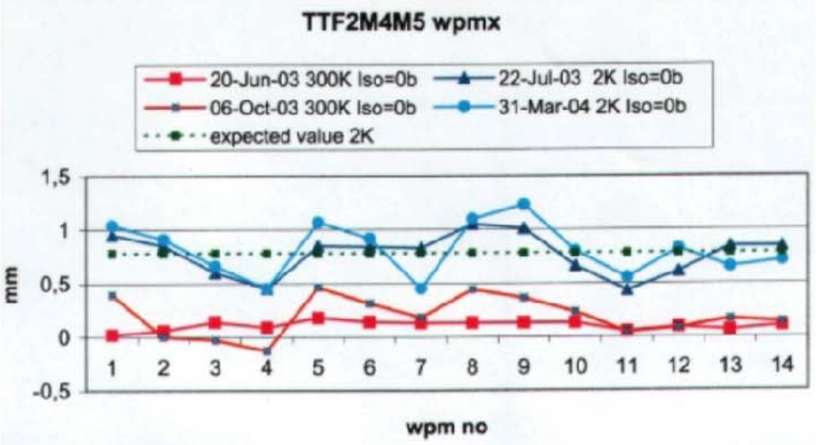
Module 1

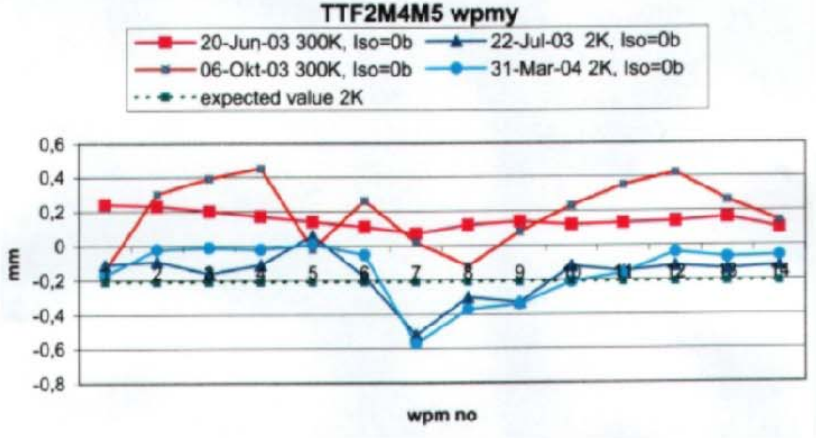


Module 2 & 3

Module 4 & 5

ACC4 & ACC5 Met Specs





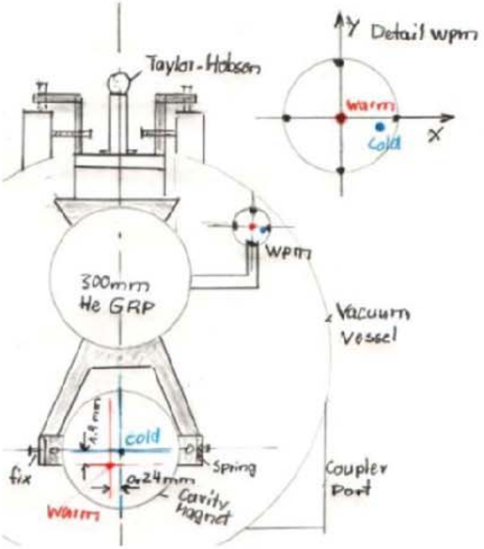
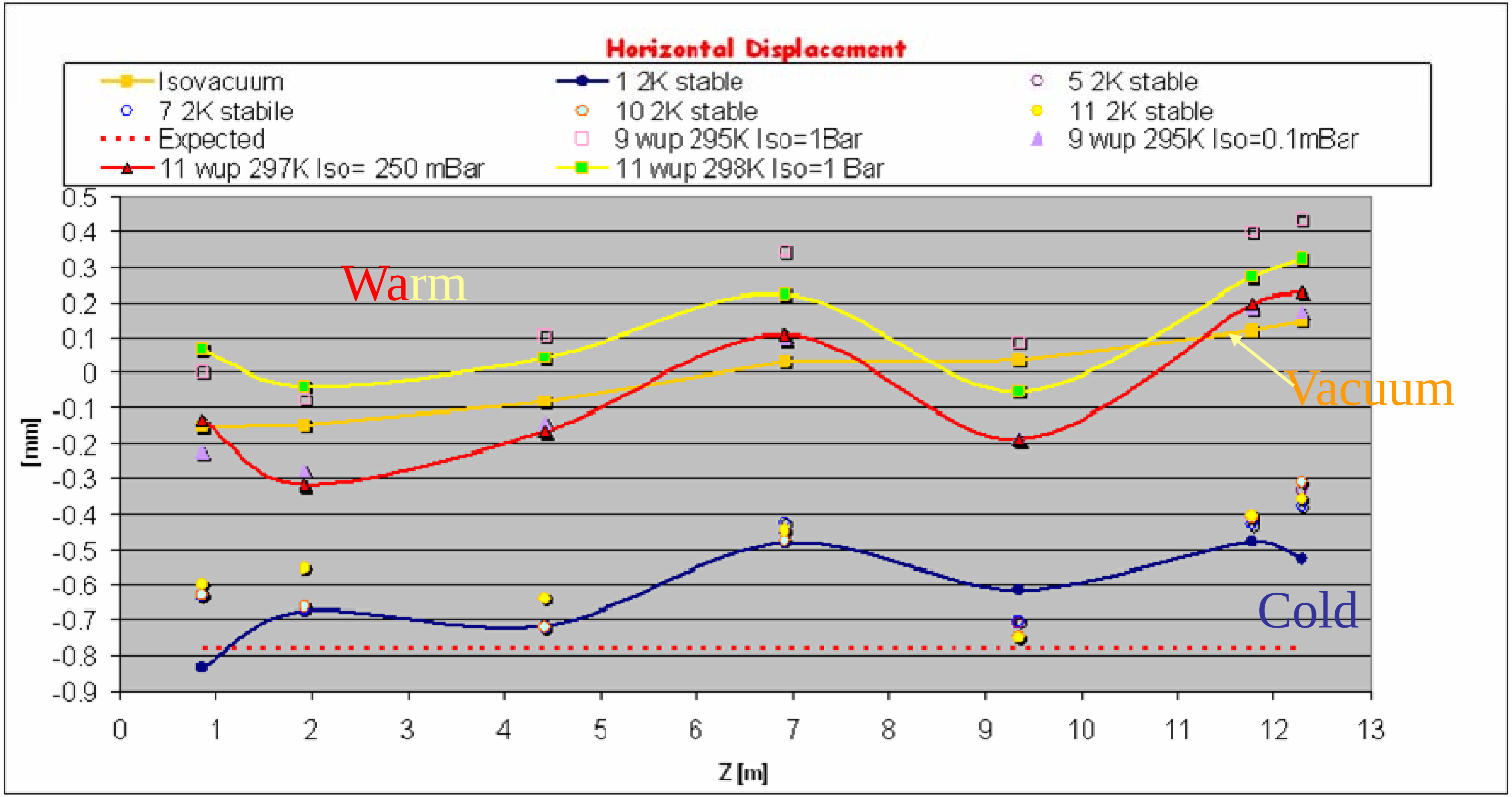


Table 1: Result Summary.

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

Cooldown and Warmup data for different cycles: Horizontal Displacements (only stable T points considered)



A. Bosotti
INFN

How you can participate → Interesting, Important things to do…

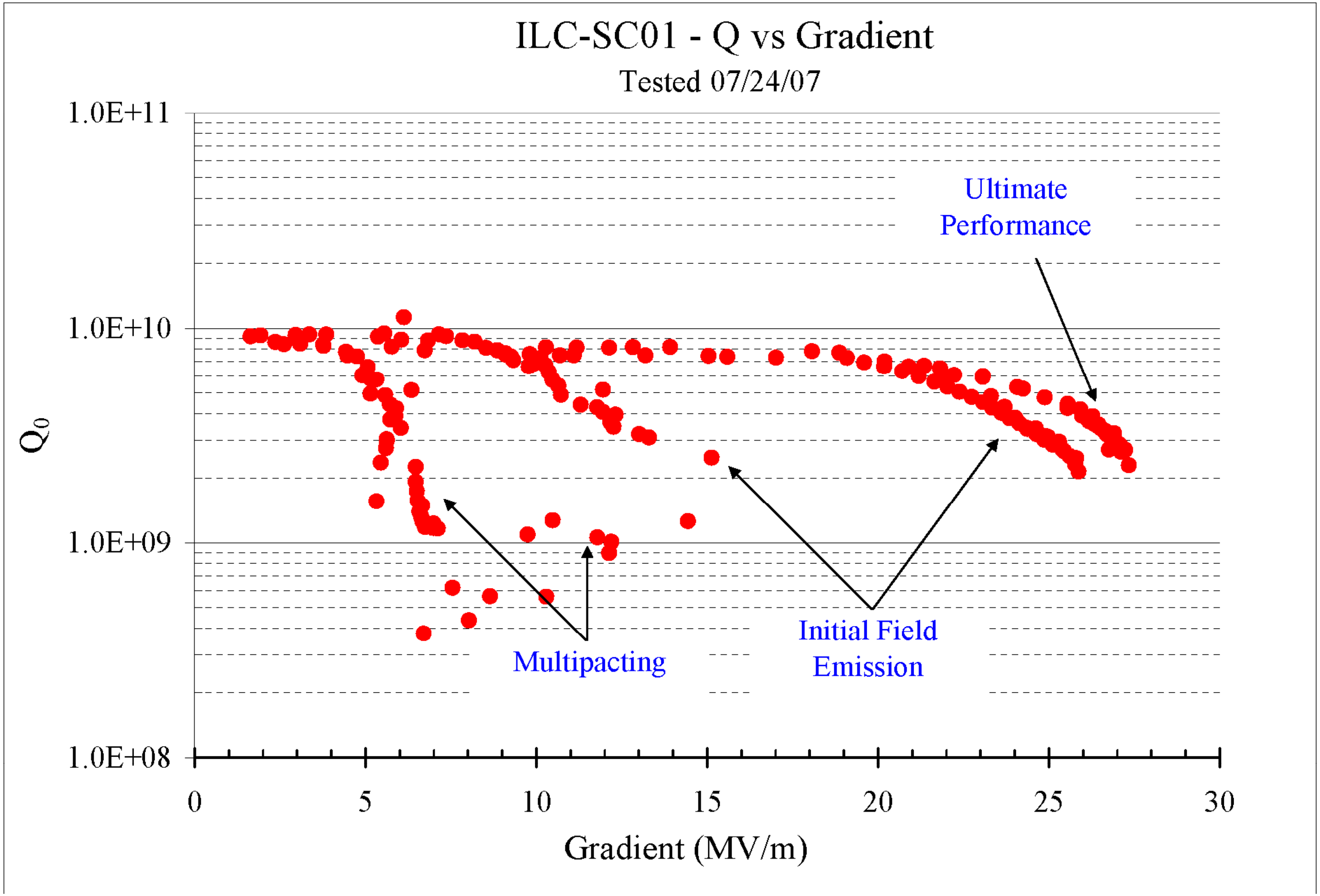
- Fortunately – the most critical and interesting R&D is close to home …
  - **In the Industrial Center and Meson area**

2. achieve the highest practical gradient

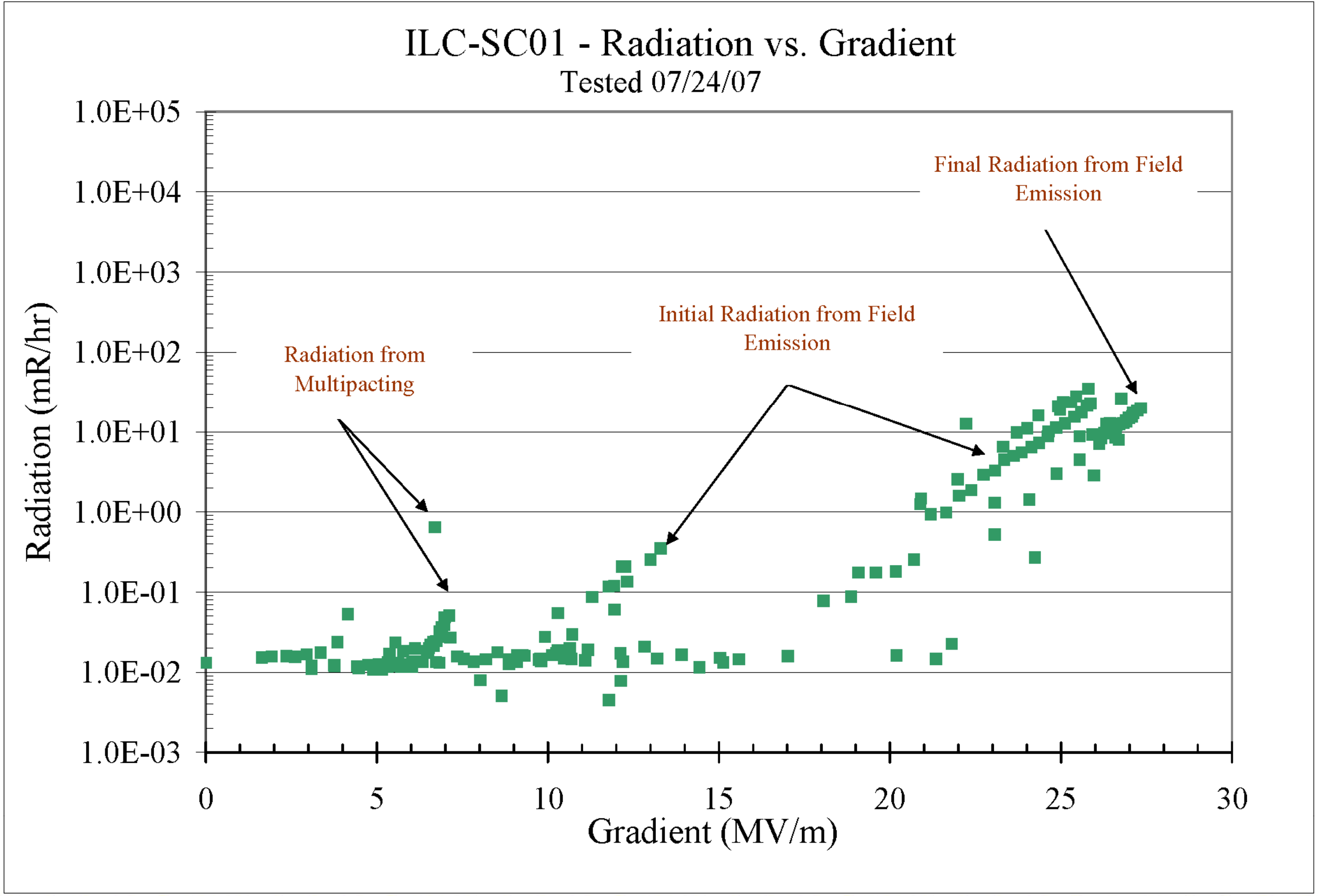
this R & D has the largest cost leverage of any of the ongoing programs.

- This topic is a primary focus of Fermilab’s development effort
  - **So far basically limited to infrastructure development**
- But – that infrastructure is now ready for use…

First 1.3 GHz Cavity tested at new Vertical Test Facility in Fermilab’s Industrial Center -single cell



First 1.3 VTS test – Radiation diagnostic:



What limits performance in a 9 cell cavity?

- Development of diagnostics and understanding related physics is a high priority
- Projects:
- (After a cavity is fabricated and processed; during test →)
  - **We have 3 basic signals to work with:**
    - Microwave
    - Thermal
    - Radiation
  - **We have 3 completely different sets of constraints:**
    - Vertical Test
    - Horizontal Test
    - Cryomodule
- We need to: Quantitatively answer the above question, using the above.

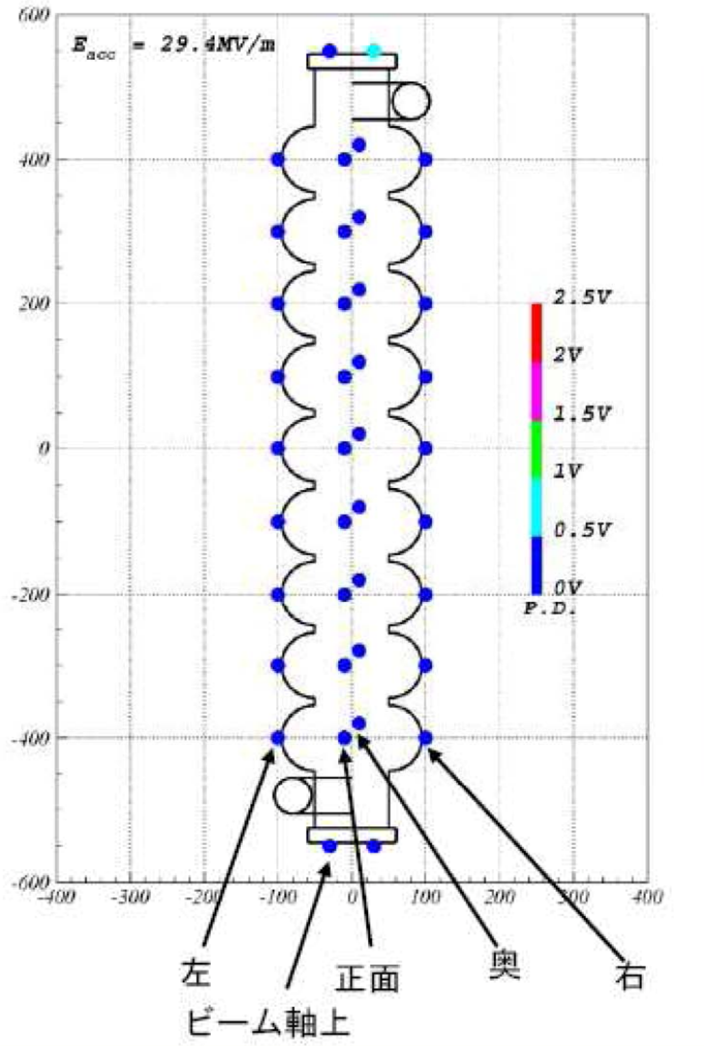
Example SCRF R& D Projects:

- Thermometry
  - Bandwidth, spatial resolution and sensitivity
- Radiation
  - Localization, energy flow and bandwidth
- Microwave
  - The independent variable in the apparatus
  - Completes the energy equation
- None of these are easy; few are under active development
  - Fermilab’s new infrastructure offers excellent opportunities

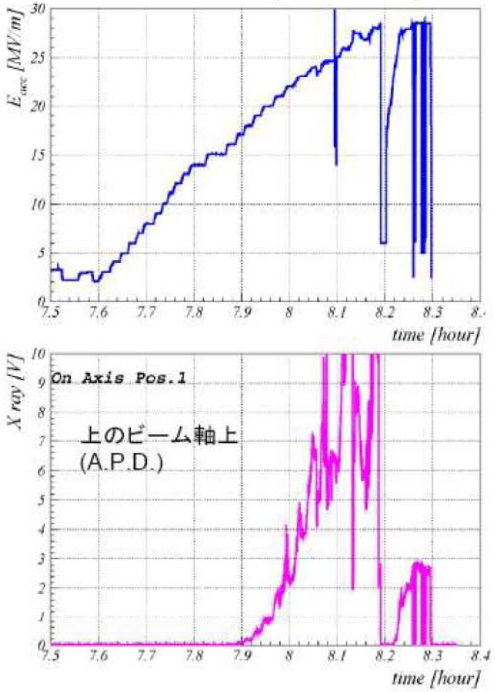
KEK field emission data

Kirk Yamamoto

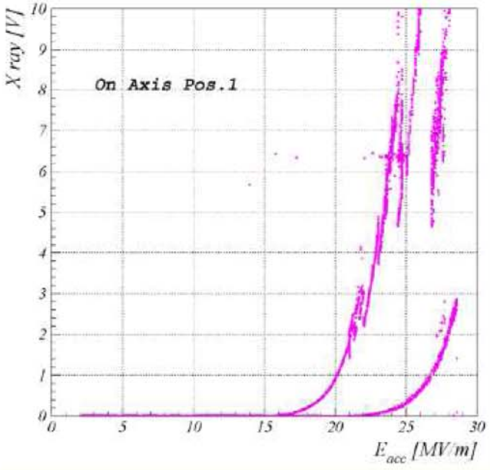
X-ray Mapping Display for STF B.C. #2 (2007/02/23)



ILC B.C. #2 (2007/02/22)



ILC B.C. #2 (2007/02/22)



- Example of something interesting to do
- Photodiodes placed around cavity
- Hamamatsu S1223-01 3.6 mm x 3.6 mm
- No thermal contact required – simple ass'y
- Excellent correlation between gradient and x-ray flux; also one FE burn off observed

List of primary limiting physical effects:

- (see talk by Hasan)
- Multi-pactor
  - **Resonant multiplication (geometry and field, also contaminants)**
- Field emission
  - **electron sources often caused by surface debris**
- Thermal ‘run-away’ – quench- due to:
  - **Poor cooling**
  - **Imperfections**
    - Inclusions , surface deformation
  - **Fundamental SCRF limits**
- Low Q due to poor surface resistance

Diagnostics – (Peter Kneisel)

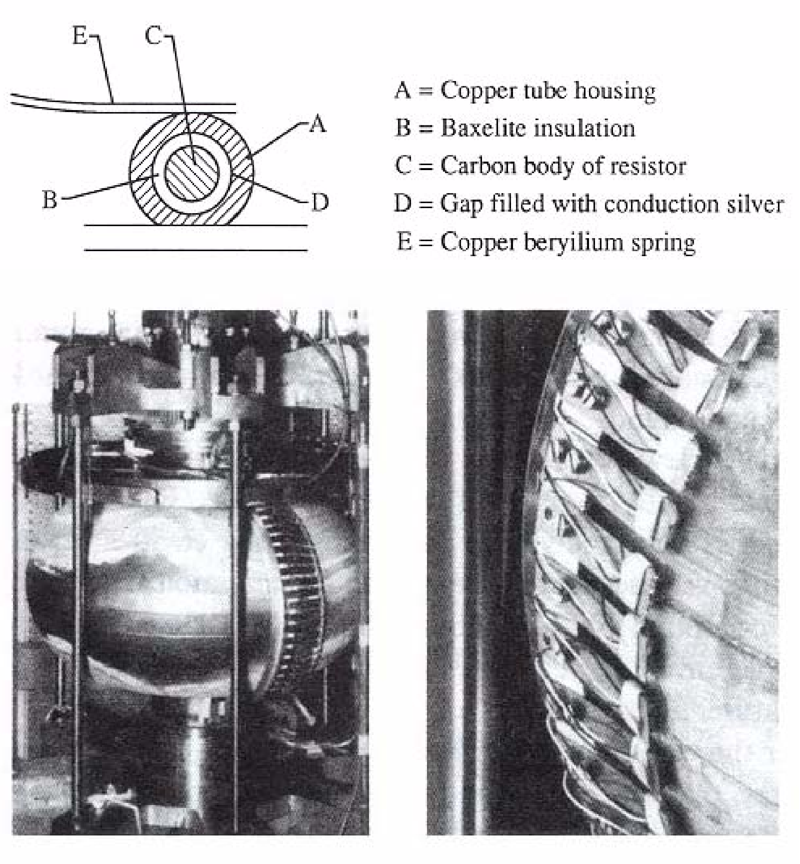
- The application of diagnostic methods allows to gain understanding of localized phenomena on a cavity surface

- Each energy loss mechanism in a sc cavity will lead to a flux of heat into the helium bath surrounding the cavity
- This heat flux raises the temperature of the intermediate helium layer between outer cavity surface and the bulk helium bath
- Qo vs Eacc gives a global picture of the behaviour of a superconducting cavity
- With an array of thermometers sliding around the cavity surface a “temperature map” can be compiled
- Conclusions about the loss mechanisms inside the cavity can be drawn.

Temperature Mapping, cont'd

- First rotating T-mapping system implemented at CERN

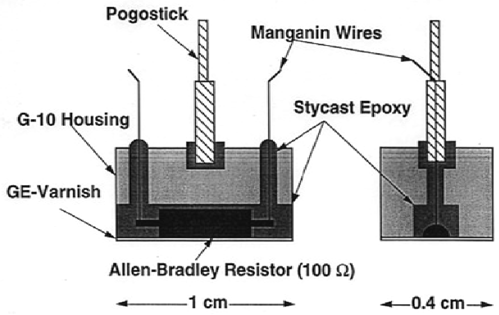
- increase in heat transfer resistance from metal to He bath
- ● absence of nucleate boiling therefore no micro-convection due to bubbles
- surface temperature increases compared to saturated He
- T-sensors are thermally decoupled

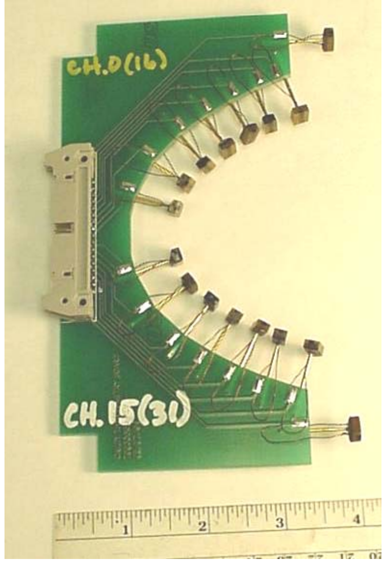


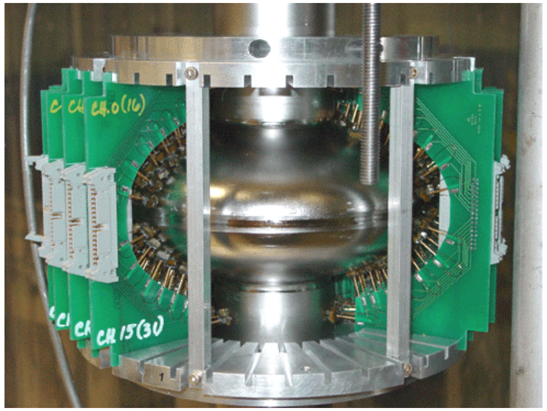
Peter Kneisel - JLAB

T-Mapping (1)

T-mapping system: ~600 Allen-Bradley C-resistors







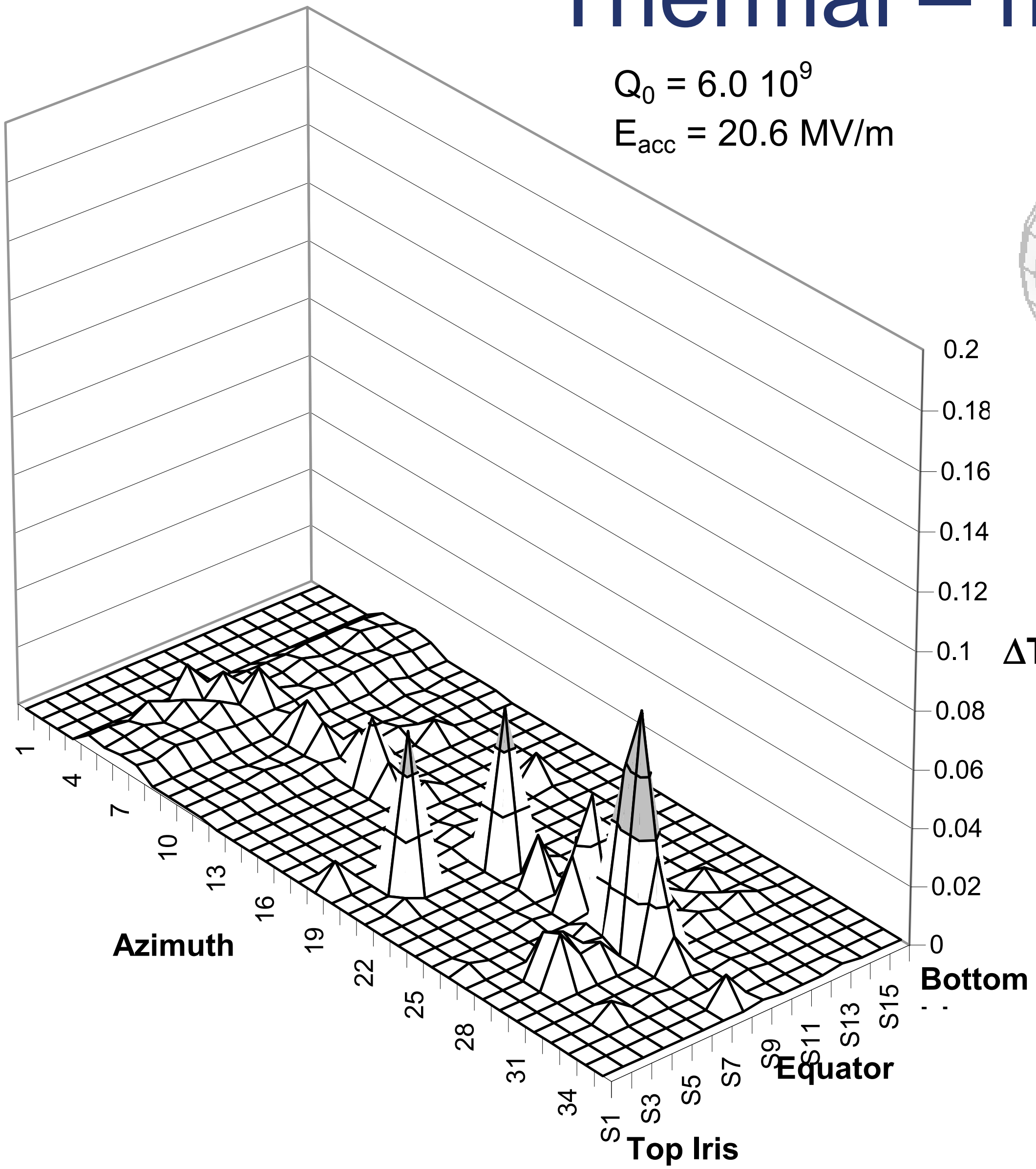
a)

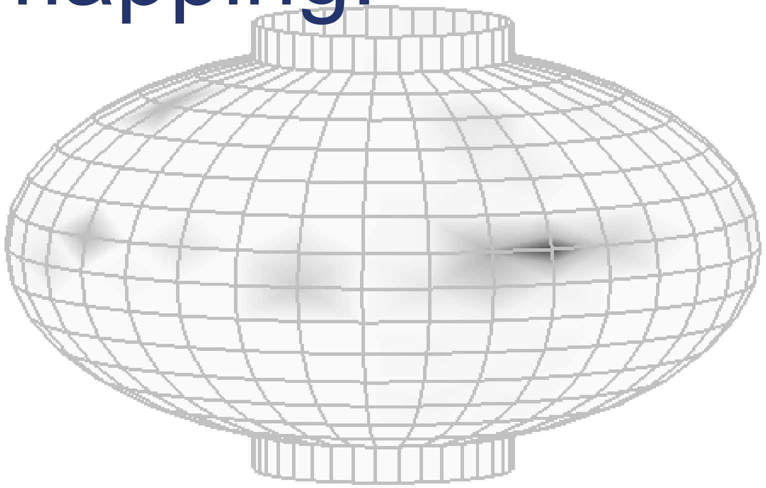
b
)

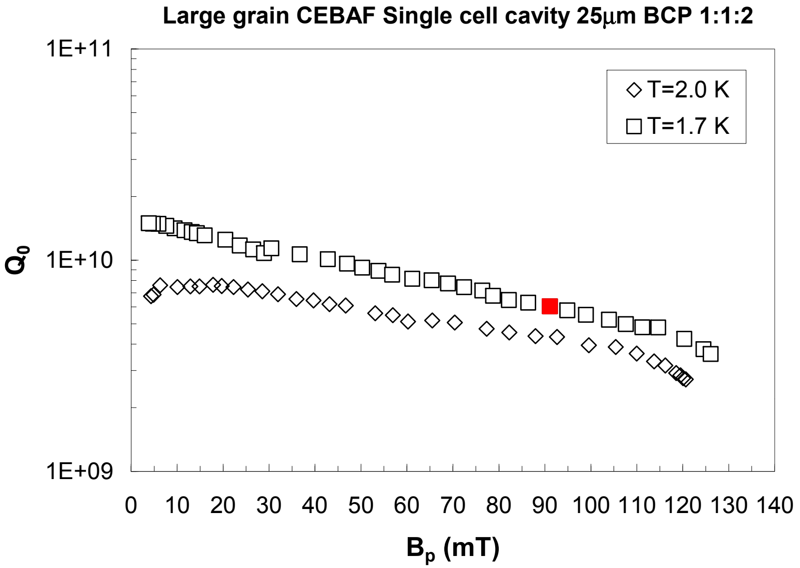
Thermal – mapping:

Q_0 = 6.0 10^9

E_{acc} = 20.6 MV/m



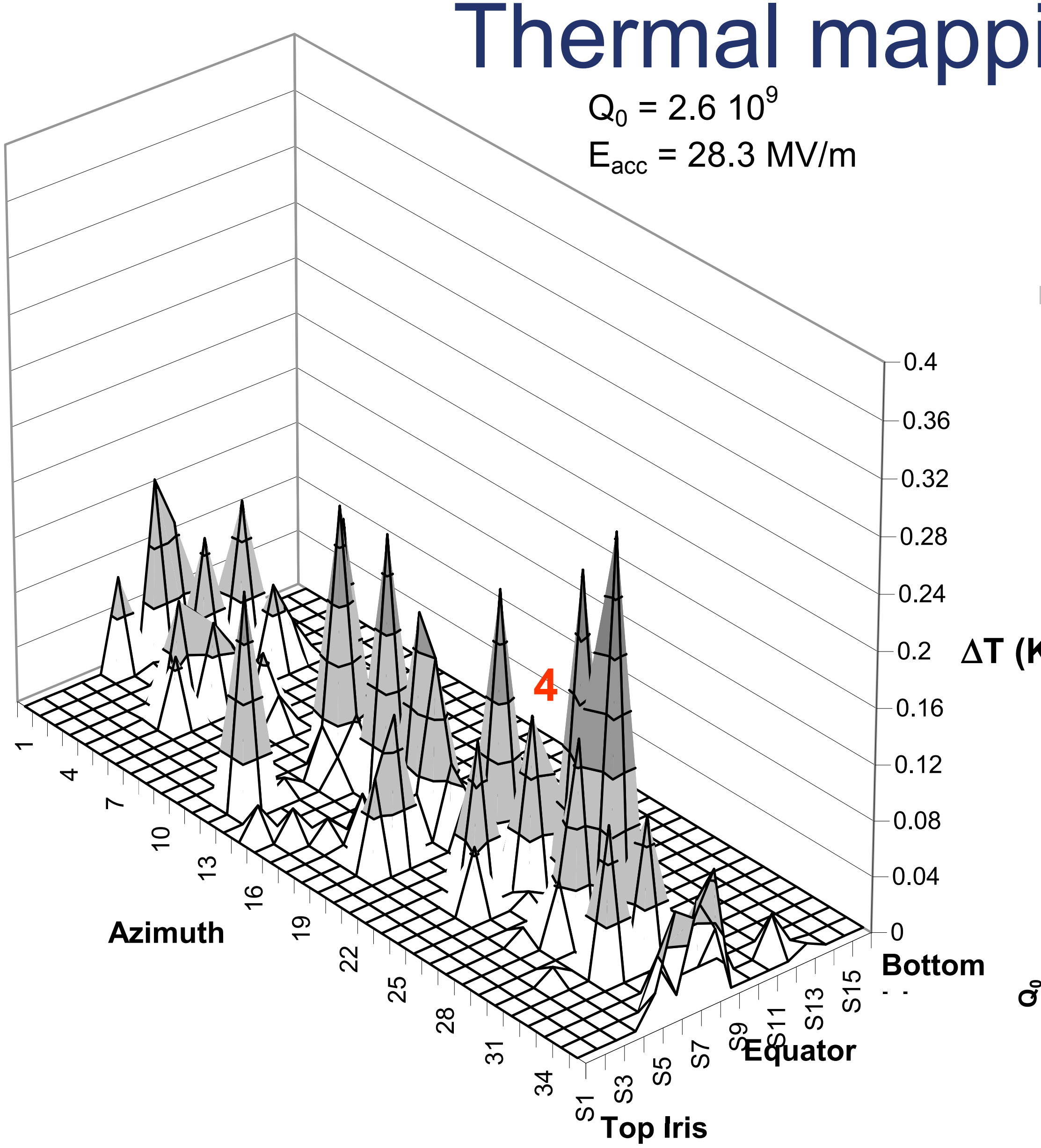


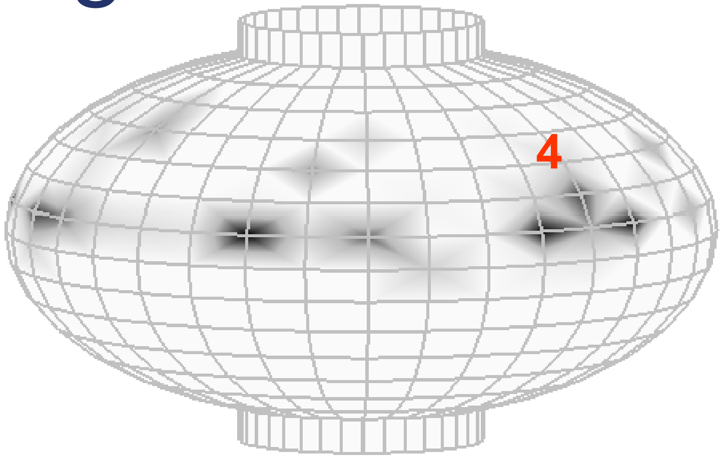


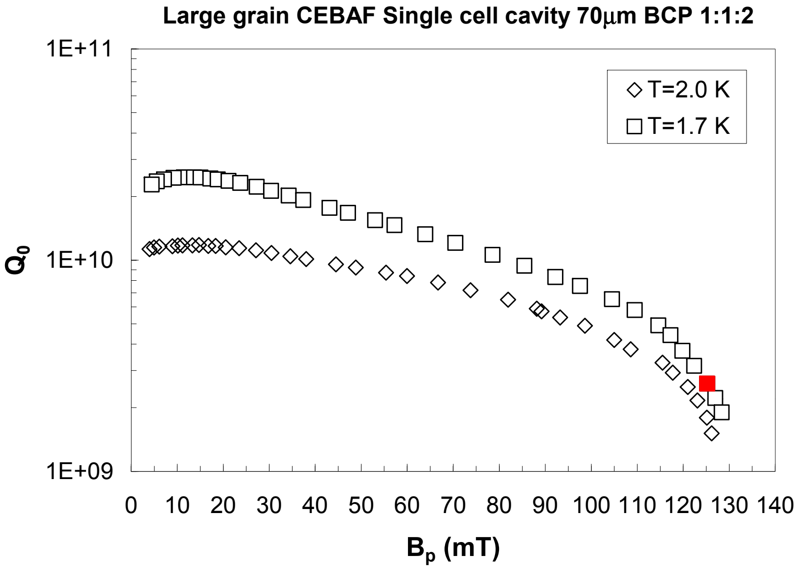
Thermal mapping: low Q

$Q_0 = 2.6\ 10^9$

$E_{acc} = 28.3$ MV/m



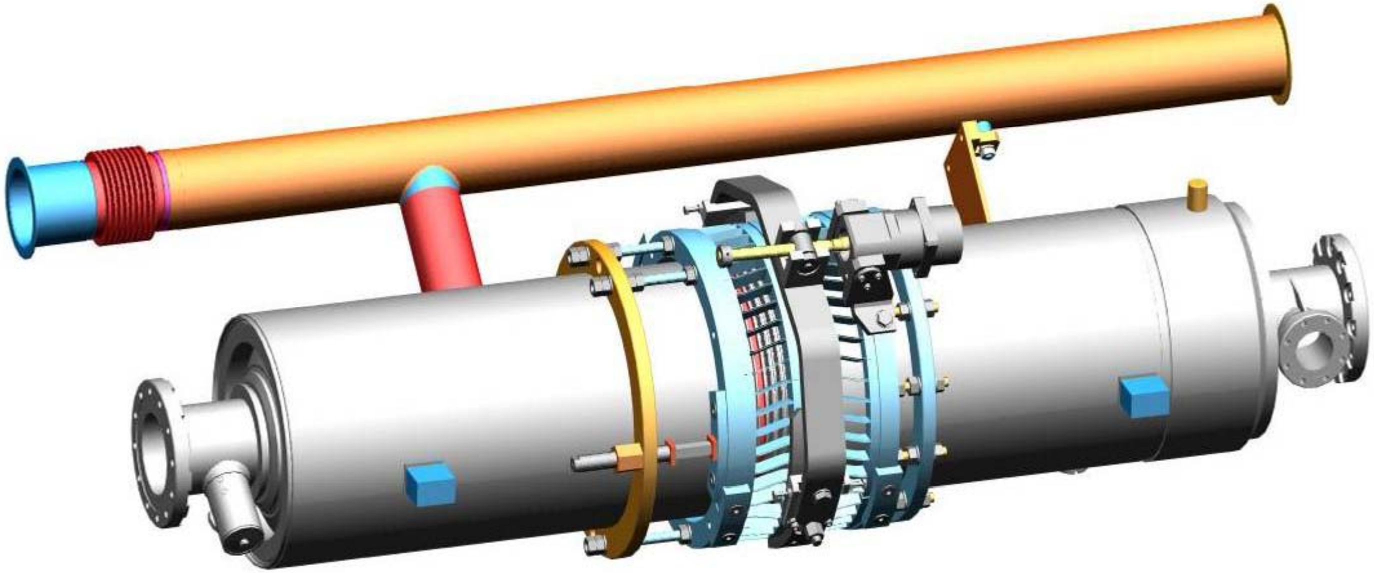


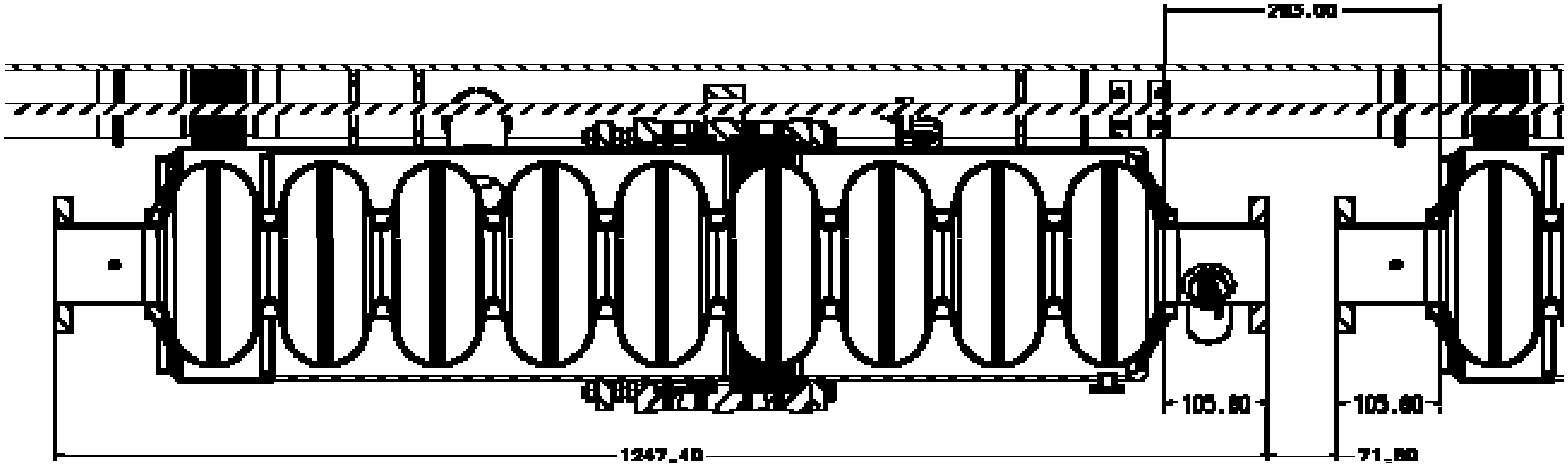


Superfluid He

- Non-contact thermal diagnostics:
- (Cannot include motorized or multi-channel contact thermometry after cavity is put into tank)
- Can thermal mapping be simplified using properties of superfluid?
  - **Could this be done after 'dressing'?**
- Imaging heat 'transients' using distributed thermometry
  - **'second sound'**
  - **Heat moves through He_2 in waves ~ 20µm/ µs**

Dressed Cavity: 3D Model and Dimensions



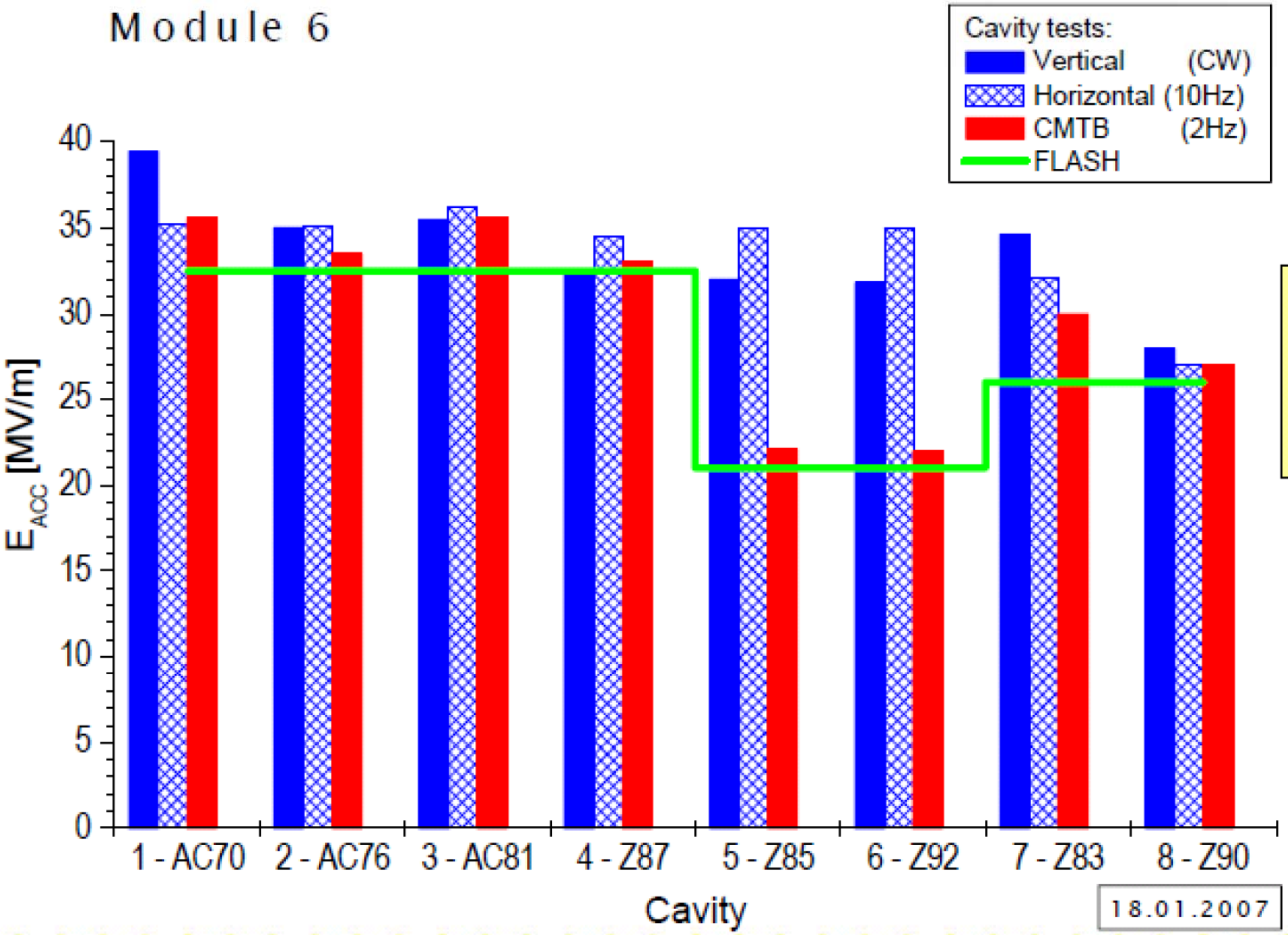


M. Ross, GDE

Cavity Performance

(courtesy D. Kostin – DESY)

By L. Lilje (DE



Averag
gradien
28 MV/

Specific Tasks – Cost

Cryomodule costs	fraction	sum
Cavity Fabrication	36%	36%
Power Couplers	10%	46%
Helium Vessel Fabrication	8%	54%
Magnetic Package (Quad)	7%	61%
Tuners	7%	68%
Assembly, Testing, Transport	5%	72%

- **(Next 7 items – to 1% level (22%)– Vacuum vessel,shields, interconnect, processing, dressing, pipes, supports, instrumentation)**

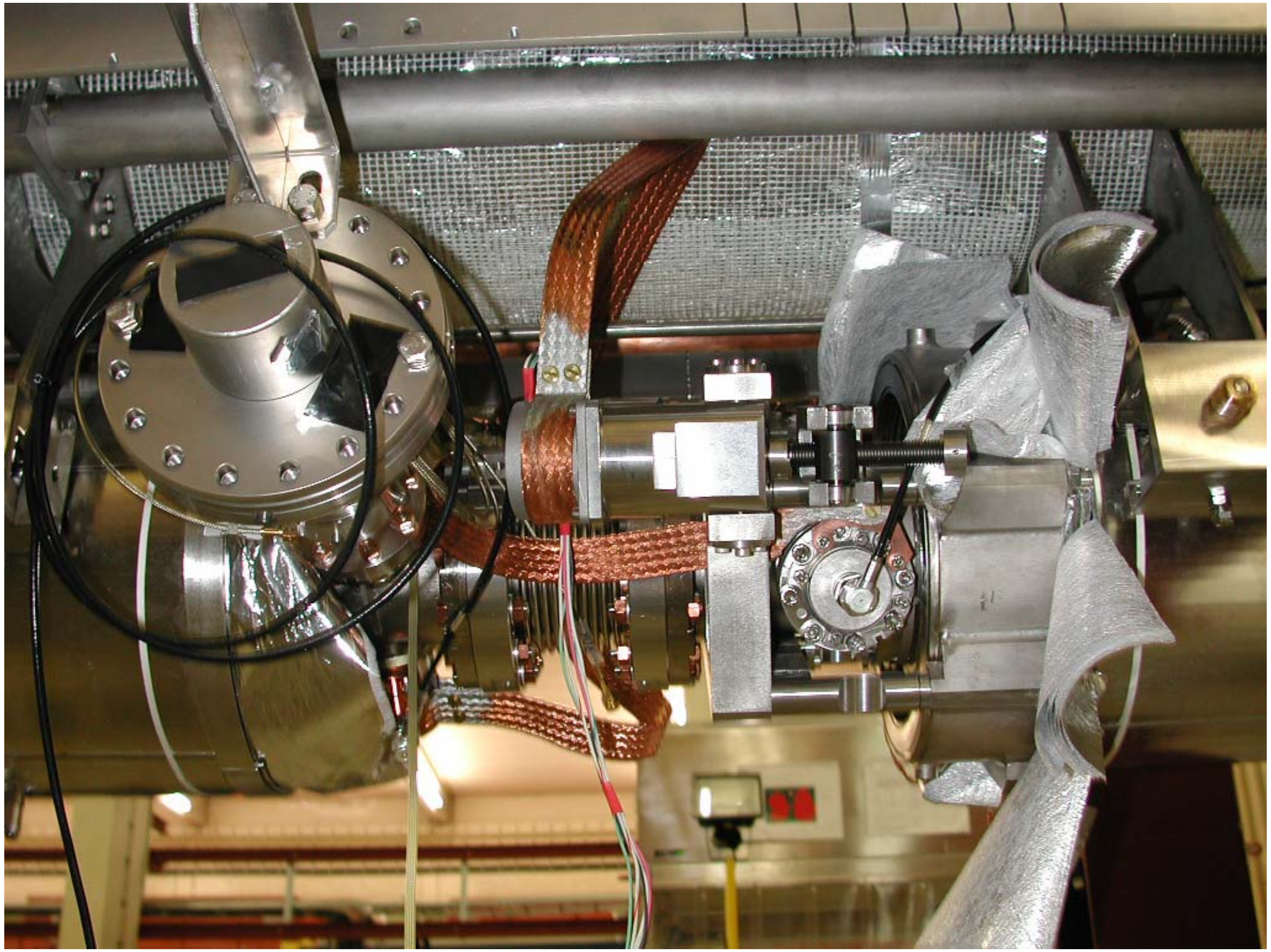
Module assembly picture gallery - 1

String inside the Clean Room

Module assembly picture gallery - 2

String in the assembly area

Module assembly picture gallery - 3



Cavity interconnection detail

Module assembly picture gallery - 4

String hanged to he HeGRP

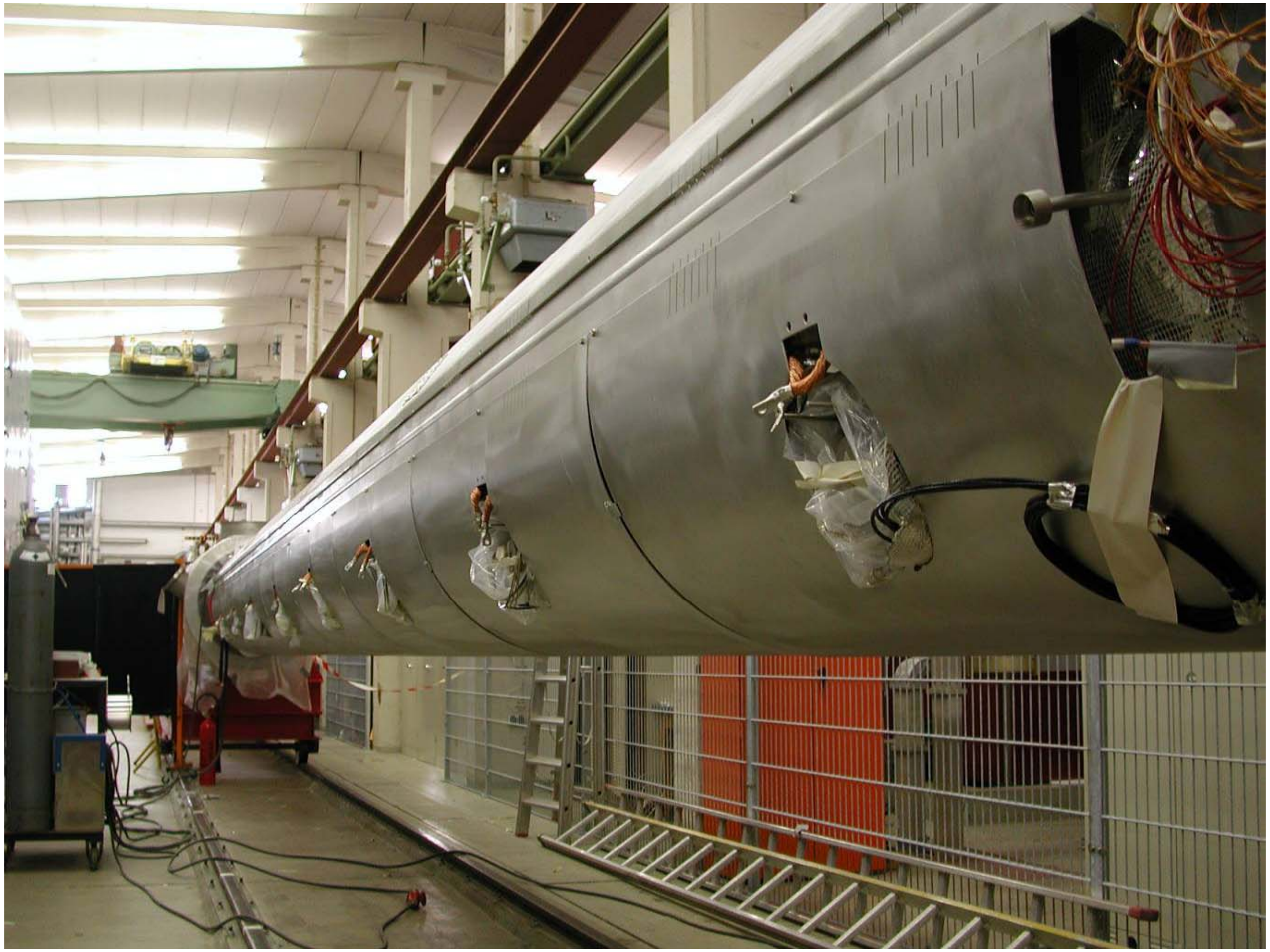
Module assembly picture gallery - 5

String on the cantilevers

Module assembly picture gallery - 6

Close internal shield MLI

Module assembly picture gallery - 7



External shield in place

Module assembly picture gallery - 8

Welding “fingers”

Module assembly picture gallery - 9

Sliding the Vacuum Vessel

Module assembly picture gallery - 10

Complete module moved for storage

Readiness / R & D Challenges

- The ILC RDR contains a complete design
  - **This machine would work…**
- BUT:
  - **We (Fermilab) need to put some backbone into an ILC plan**
    - Major goal of the ‘ILC Engineering Design Phase’
  - **and push the technology as far as we can**
- and capture the advantages we have.