Linear collider:Main linac Potential R&D items

- RF technology:
    - Cavity design, breakdown limits
    - Wakefield design and measurement
    - Power sources
- Beam dynamics
    - Instrumentaion and diagnostics
    - Simulations
    - Vibration suppression
    - Feedback systems
    - Pre-linac collimation

G. Dugan
March 11, 2002

Linear collider:Main linacs R&D -rf technology

- Fundamental breakdown and field emission limits in rf cavities, and rf cavity/coupler design for reduced ratio of peak/surface field:
  - TESLA
  - X-band
  - 30 GHz
- Wire measurements of structure impedances
- High power sources for rf (X-band, 30 GHz)

Linear collider:Main linacs R&D: TESLA cavities

- Reaching higher gradients thru surface treatments
- Fundamental research into the causes of field emission and quenching
- Following slides from L. Lilje (DESY) at LC’02

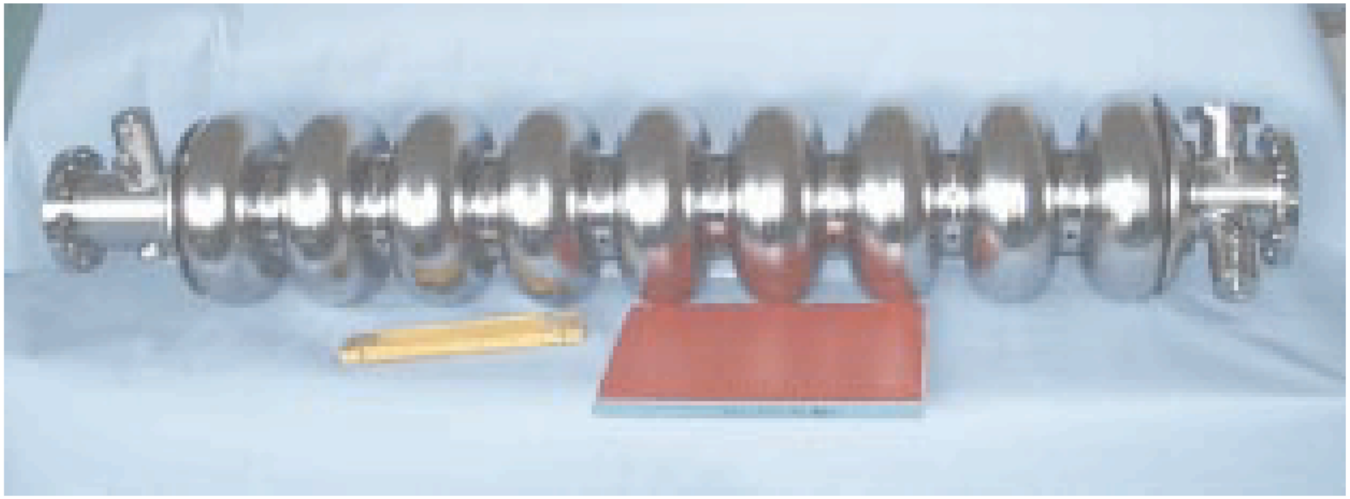


Figure 1: The 9-cell niobium cavity for TESLA.

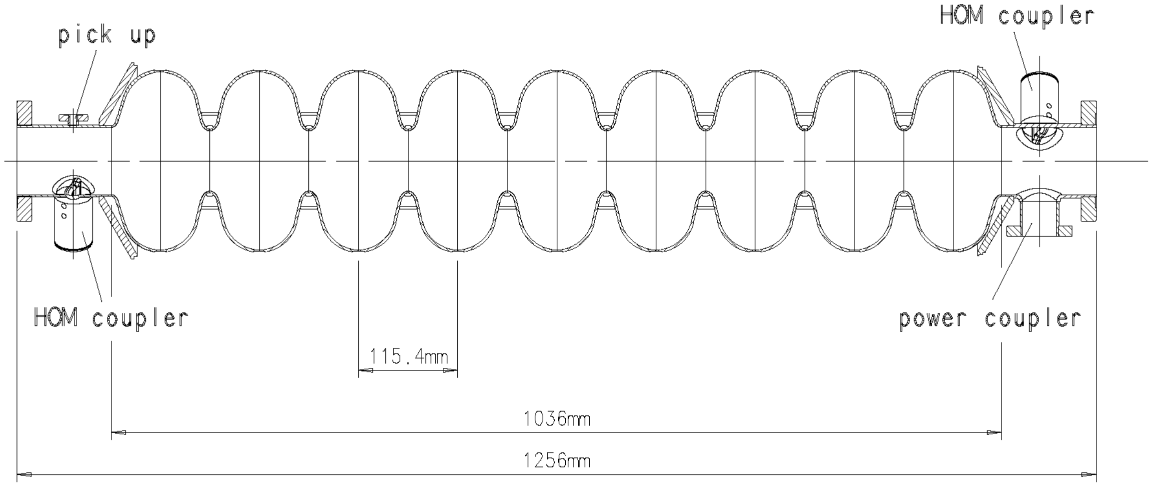
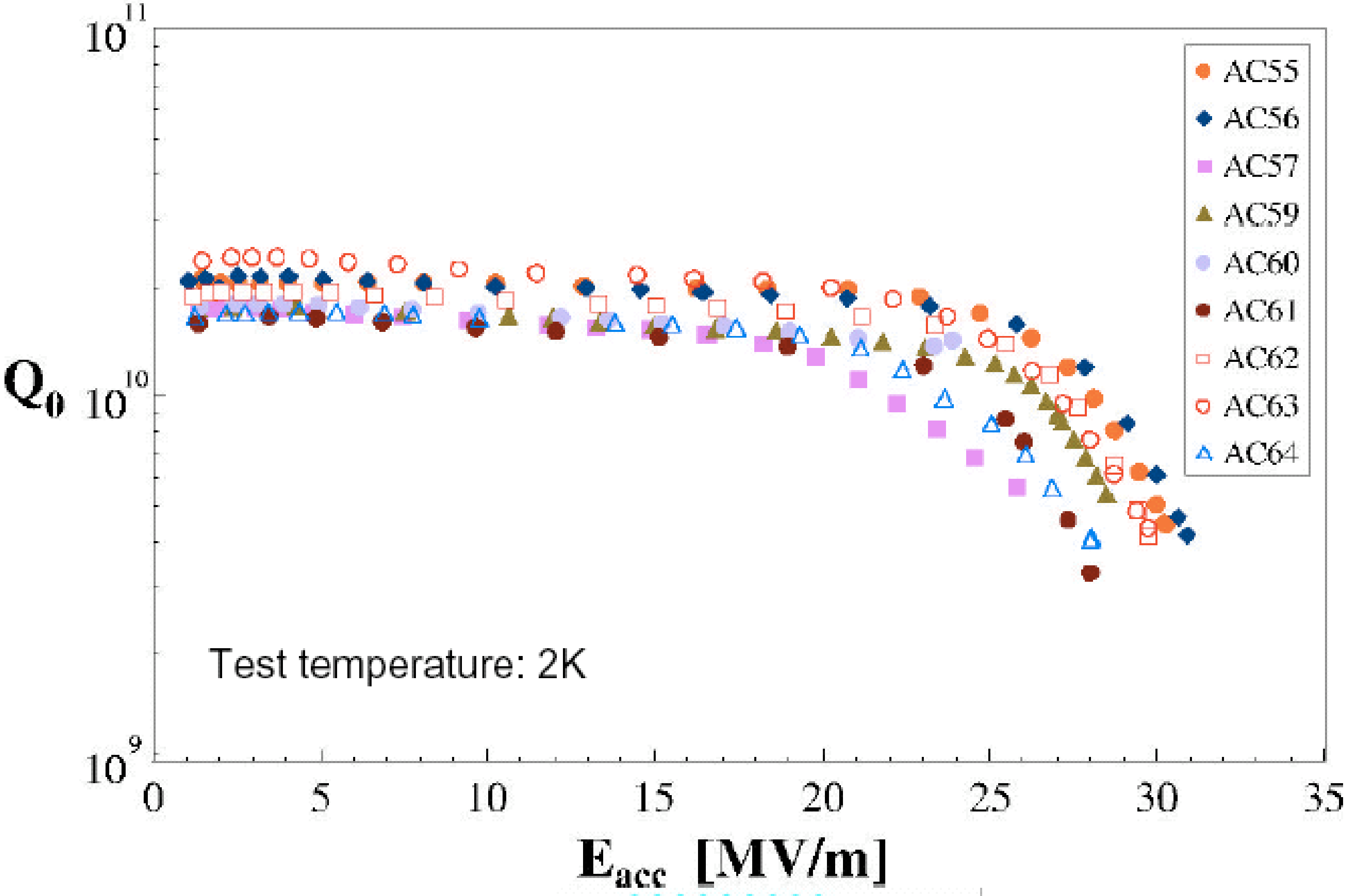
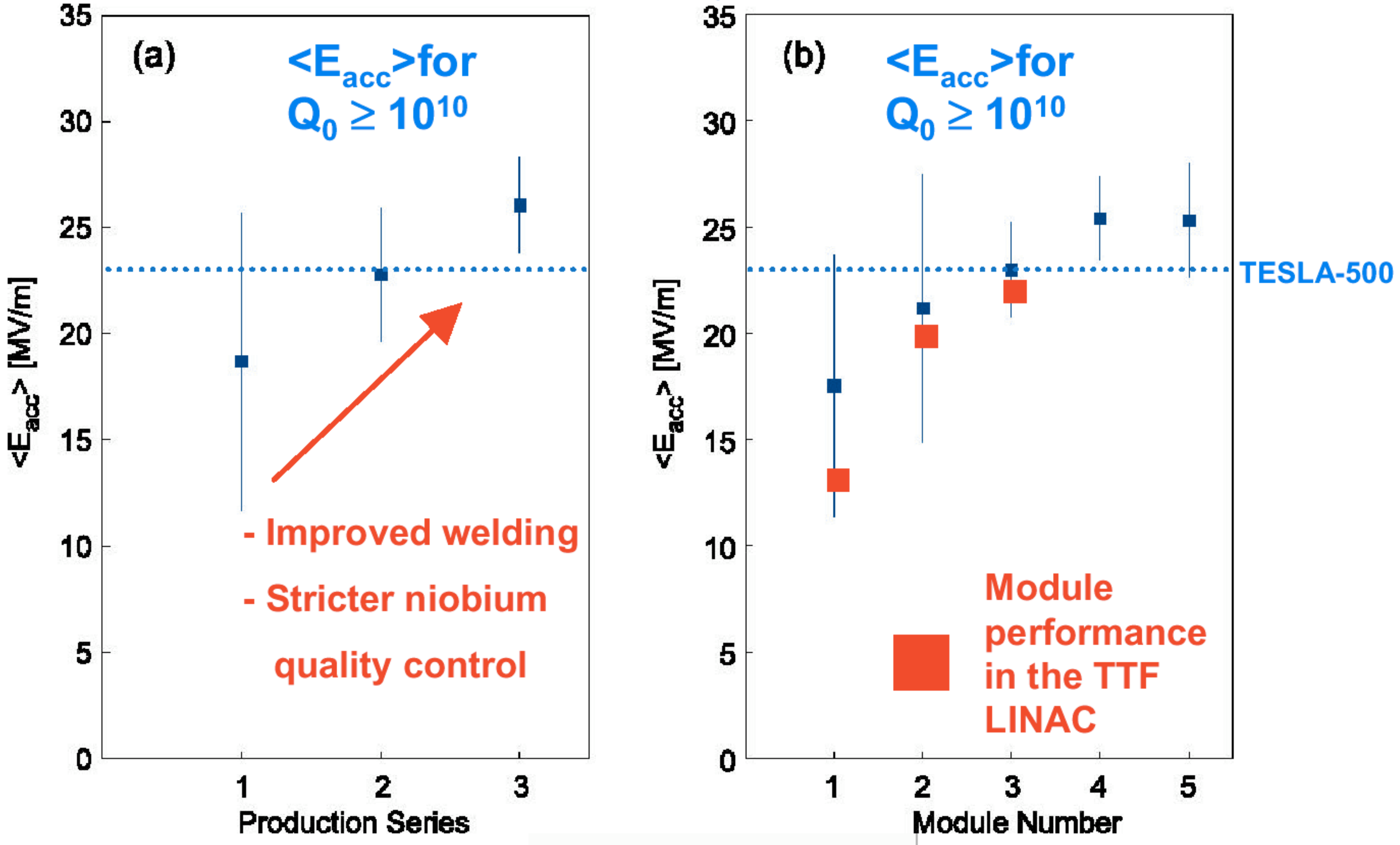


Figure 2.1.3: *Side view of the 9-cell cavity with the main power coupler port and two higher-order mode couplers.*

Latest production of TESLA-type nine-cell cavities



Results of cavity productions



$\langle E_{acc} \rangle$ for $Q_0 \geq 10^{10}$

- Improved welding

- Stricter niobium quality control

🟥 Module performance in the TTF LINAC

Results on single-cell niobium cavities

- **More than 35 MV/m** achieved with several different manufacturing techniques:
  - Electron-beam welding
    - KEK, JLab, CERN, 2 industrial companies
  - Hydroforming
    - pure niobium
    - Nb/Cu clad mateirial (etched)
  - Spun
    - pure niobium
- **Exposed cavities to air and nitrogen** - No difference after 2 and 15 month respectively

Review of different surface preparations

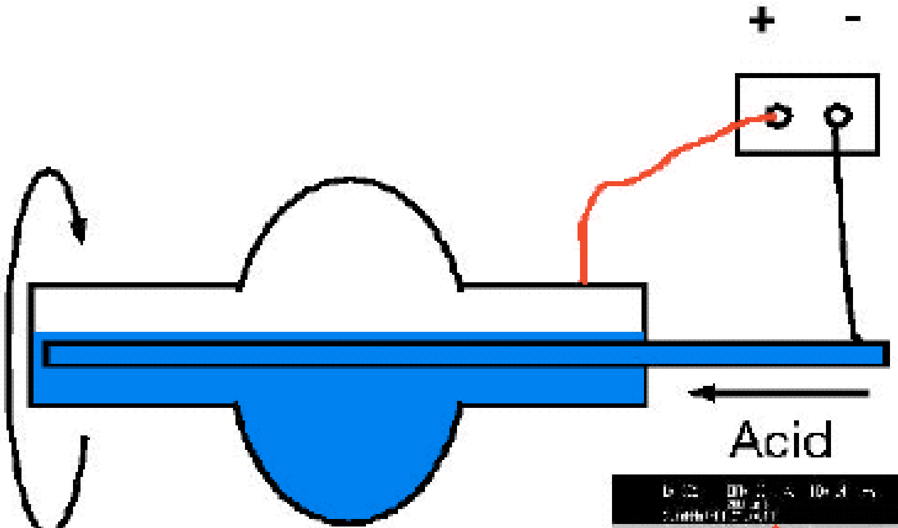
– Chemical Etching

- simple process
- typical roughness r_a=1µm
- Problem: grain boundaries are etched preferentially

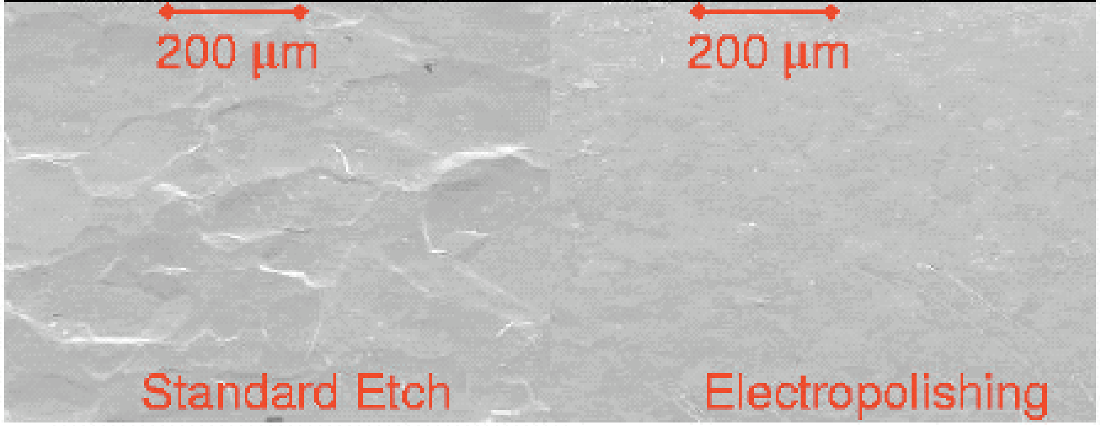
– Electropolishing

- slightly more difficult process (high current, hydrogen gas production)
- typical roughness r_a=0,1µm
- Advantage: grain boundaries are smoothened

Electropolishing of 1-cell cavities
(Scheme)

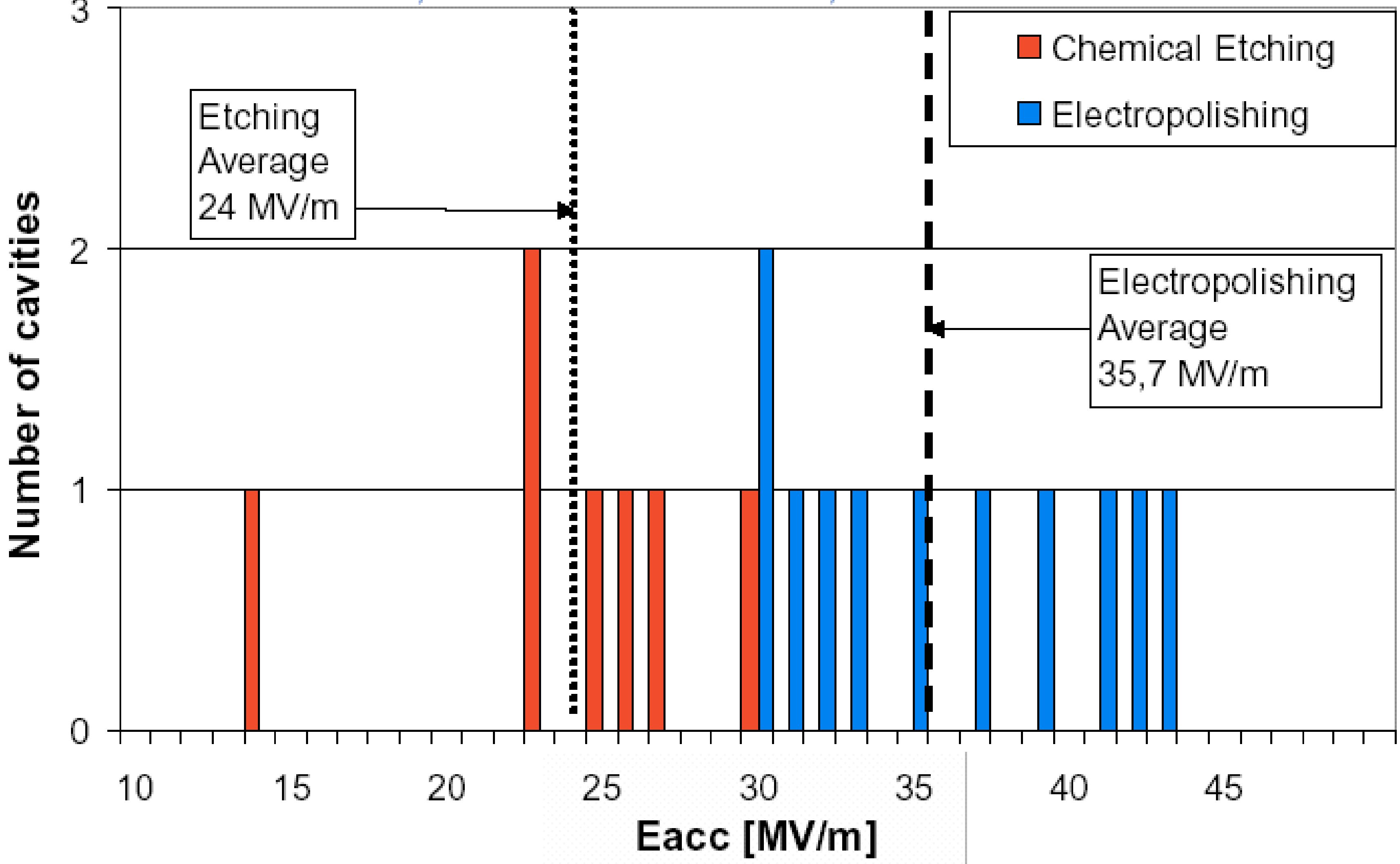


- EP electrolyte
- 90 % H_2SO_4
- 10 % HF
- 30 °C
- 0,5 µm/min removal of material



Etching versus Electropolishing

EP at CERN, Measurements at CERN,CEA and DESY 2000/2001

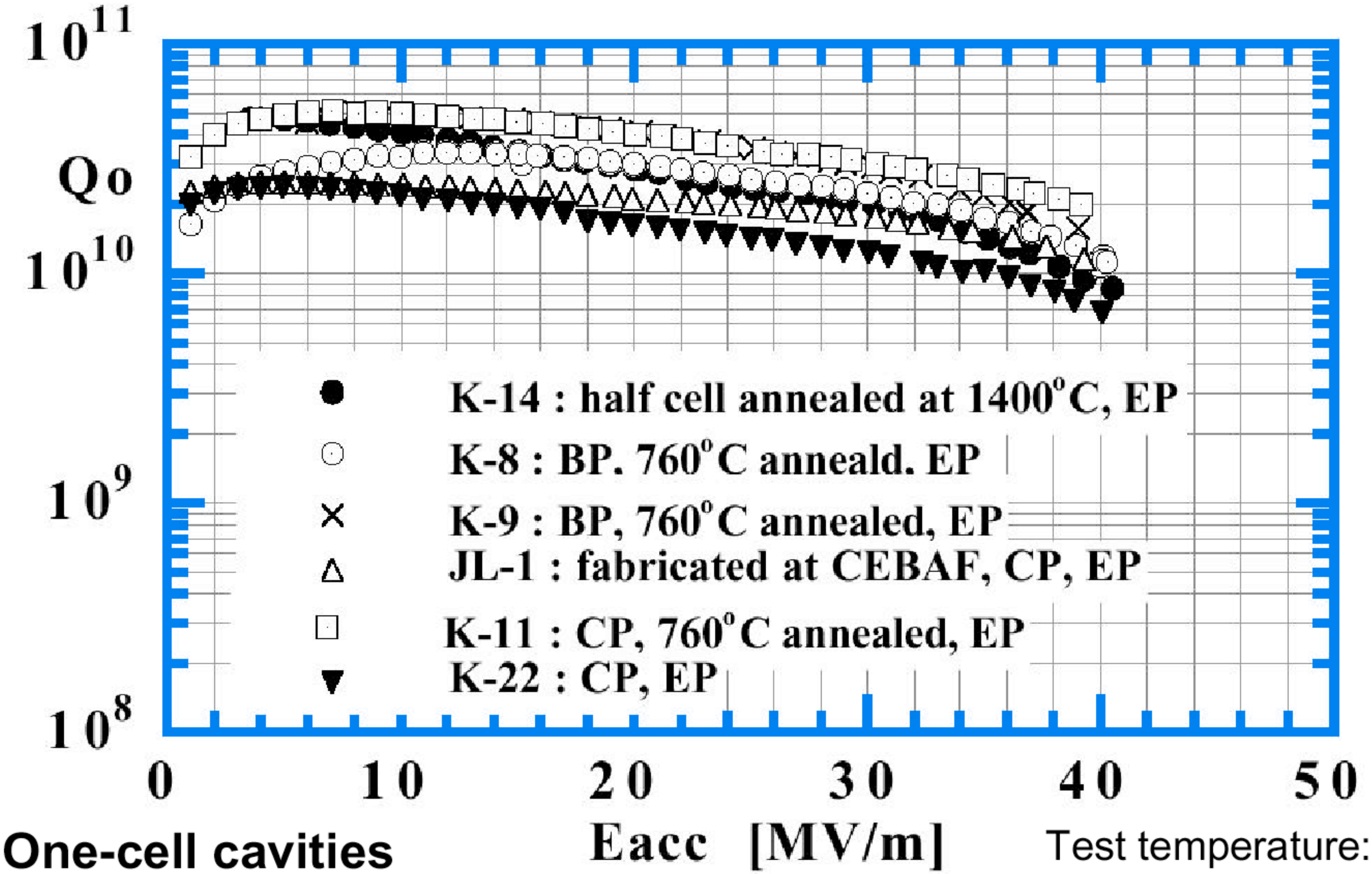


Etching Average 24 MV/m

Electropolishing Average 35,7 MV/m

KEK results for electropolished niobium cavities

K. Saito et al. KEK 1998/1999



One-cell cavities

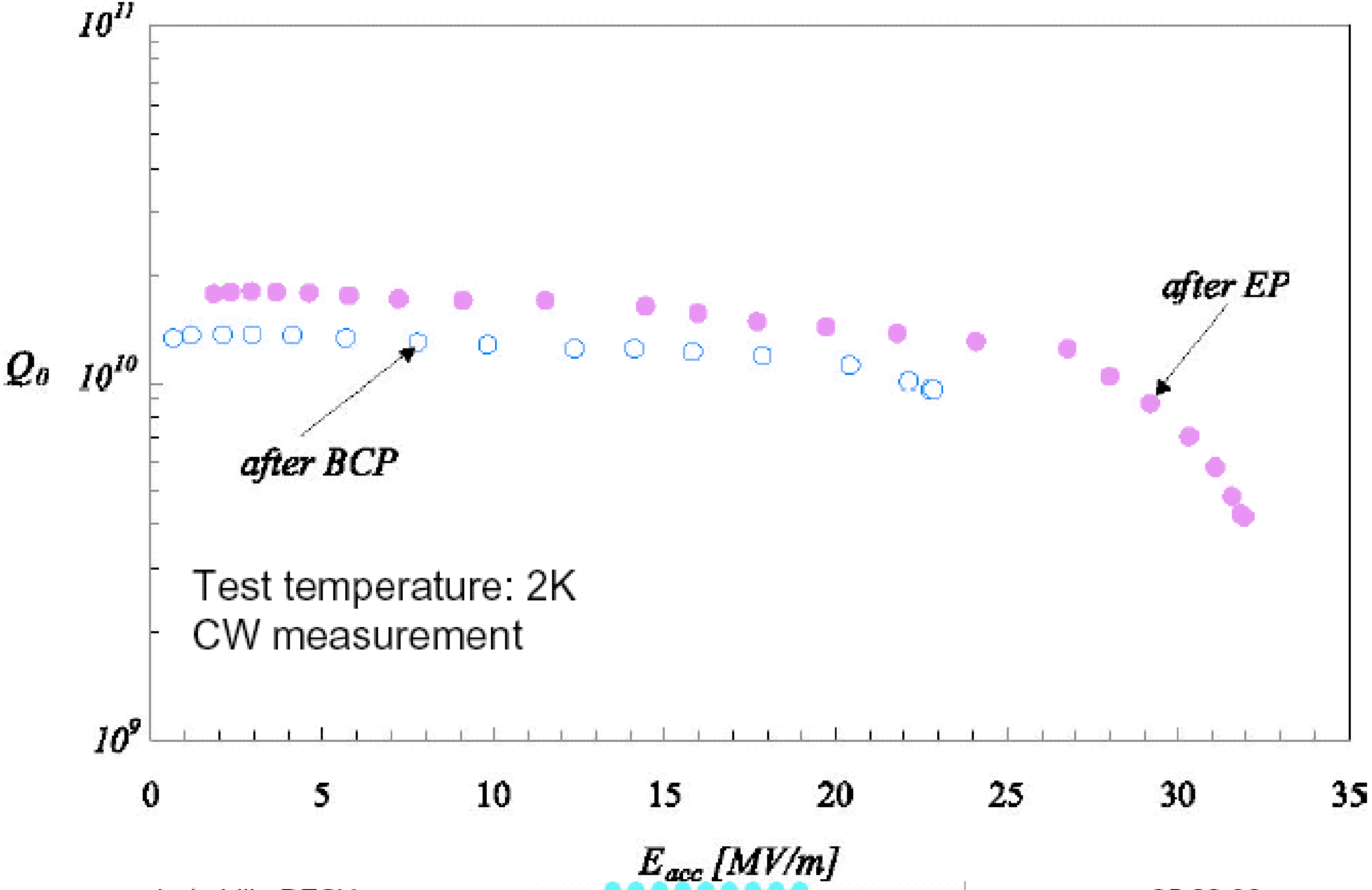
Test temperature: 1,6 K

Multi-cells niobium cavities

- Improving the surface quality has yielded very good results on **several single-cell niobium cavities**
- Challenge: Transfer the technology to multi-cells
- Therefore, we need development:
  - show **technical feasibility** (higher current during EP, homogenous surface finish) -> **OK**
  - check whether post-purification in 1400 C is really necessary -> Unfortunately, it looks like we still need it
  - test EP on several nine-cell (and eventually 2x9) cavities

Electropolished TESLA nine-cell cavity

EP at Nomura Plating and KEK, Test at DESY



Test temperature: 2K
CW measurement

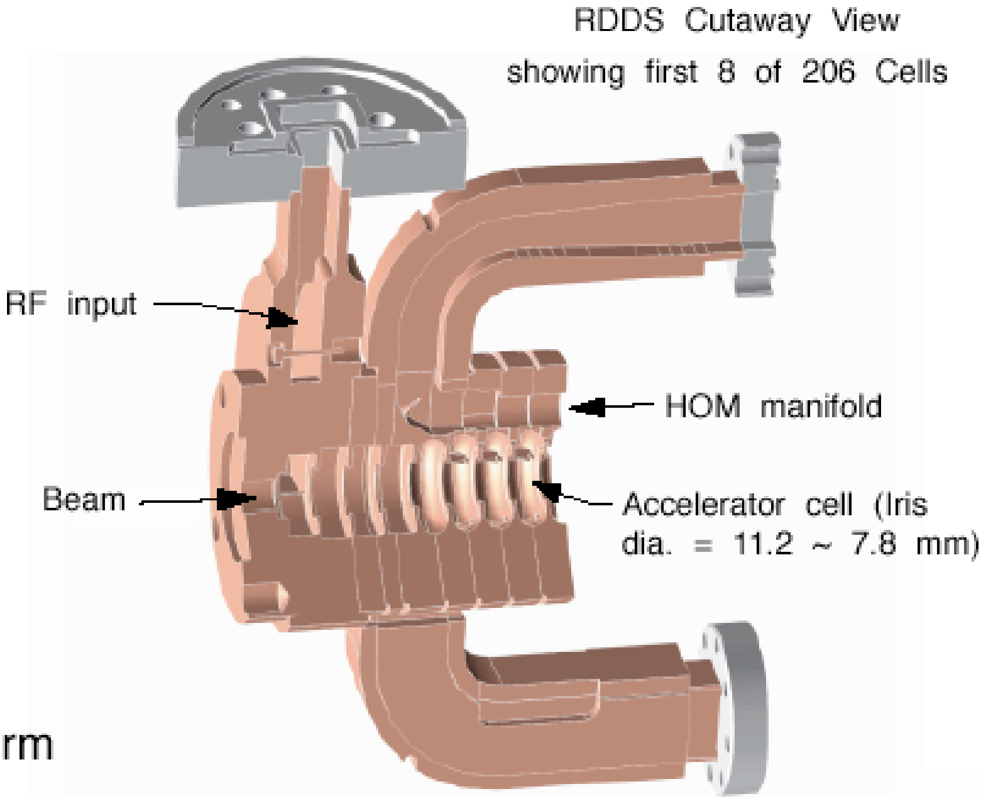
Multi-cells niobium cavities (ctd.)

- Program with KEK to electropolish nine-cells:
  - “Proof-of-feasibility“ cavity (1400°C fired)
    - » have shown that polishing is technically feasible
    - » bright, shiny surface aspect in full cavity
    - » 32 MV/m in CW measurement
  - 4 with 800°C firing only
    - – 2 cavities tested so far:
      - » between 15 - 20 MV/m, field emission loaded
      - » new test with additional high pressure rinsing
      - » if no good peformance do the 1400 °C firing
  - 4 with 1400°C
    - – 1 tested:
      - » 29 MV/m in CW measurement, power limited
- **New EP setup** at DESY until spring this year
  - reduce the distance from EP to test cryostat by factor 10^6 (going from 20000 km to 20 m...)
  - possibility to treat 2x9 superstructures
- get some statistics on multi-cell cavities until end of this year

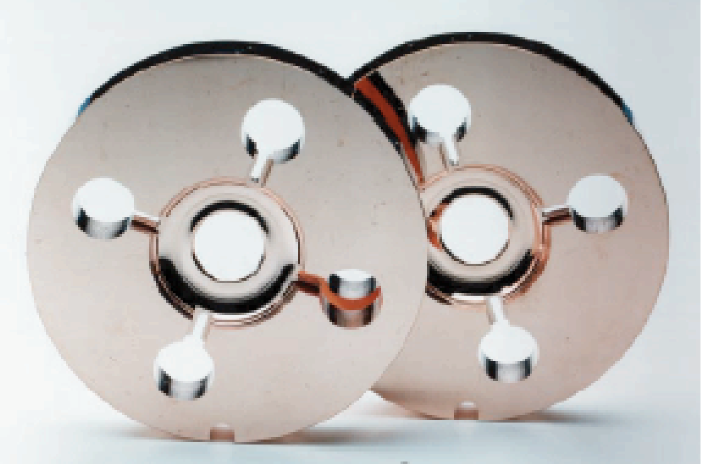
Linear colliders: R&D on X-band warm rf

- Voltage breakdown limits-the baseline RDDS X-band structures have shown evidence of breakdown damage at gradients as low as 50 MV/m.
- It gets worse as the gradient is increased.
- There is evidence to believe that it is related to both the surface field and the local group velocity
- Slides following from talks by N. Tobe, C. Adolphsen, R. Jones at LC’02.

NLC/JLC Rounded Damped-Detuned Structure (RDDS)



- Made with Class 1 OFE copper.
- Cells are precision-machined (few μm tolerances) and diffusion-bonded to form structures.
- 1.8 m length chosen so fill time ~ attenuation time ~ 100 ns.
- Operated at 45 deg C with water cooling. RF losses are about 3 kW/m.
- RF ramped during fill to compensate beam loading (21%). In steady state, 50% of the 170 MW input power goes into the beam.


Two RDDS cells

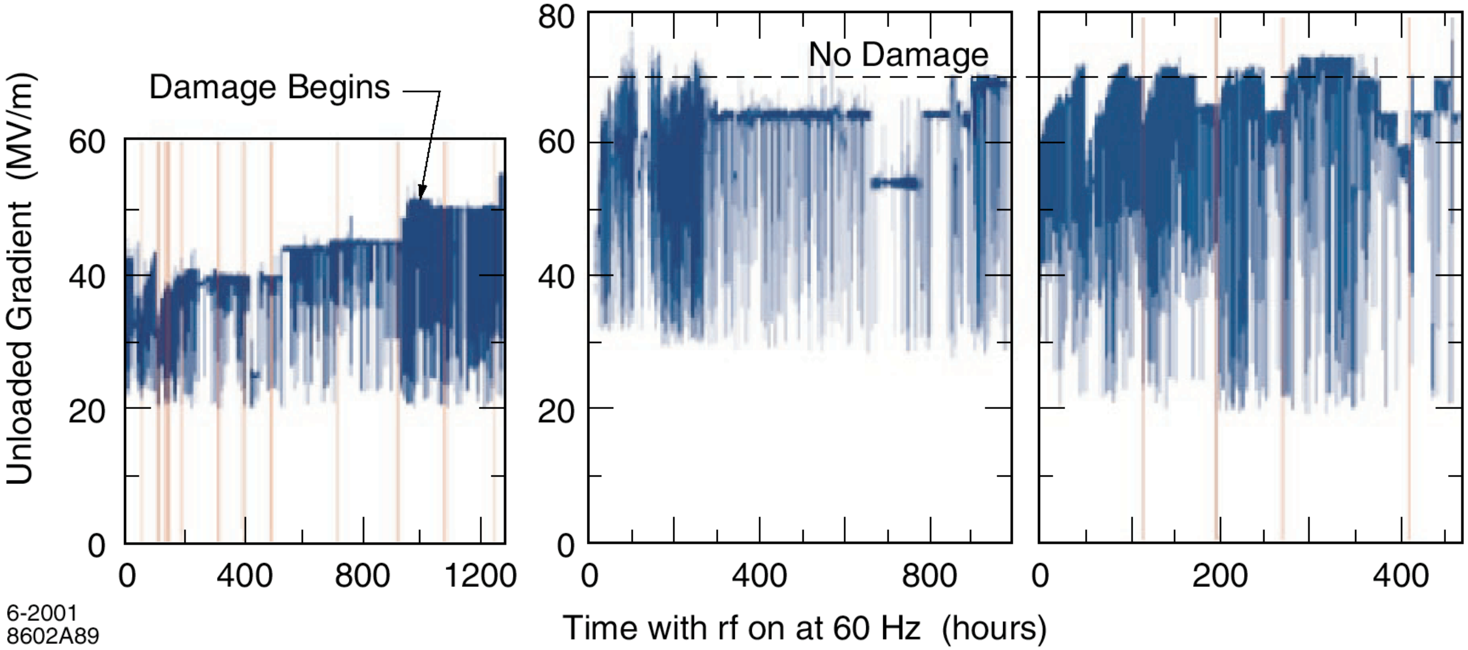
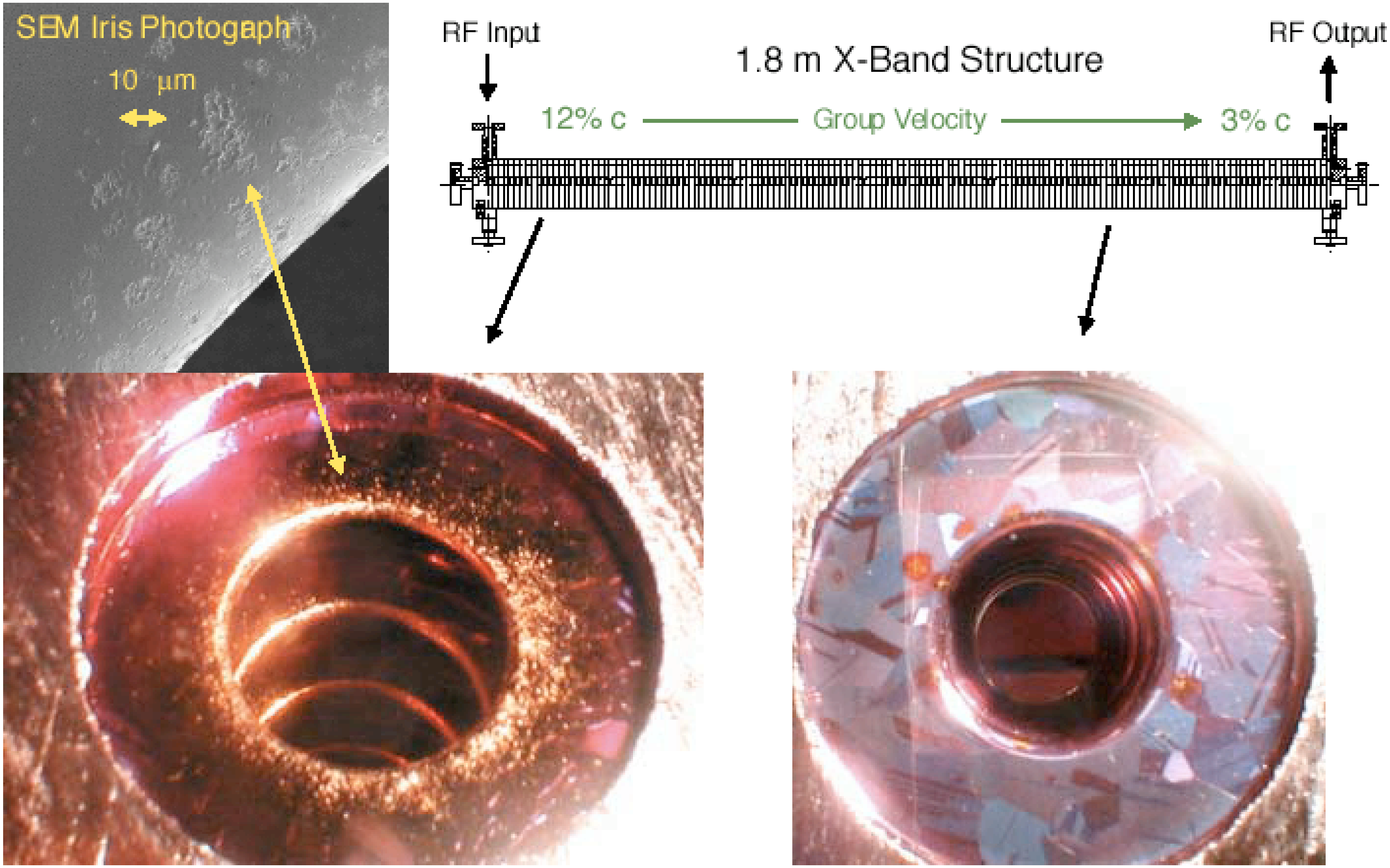
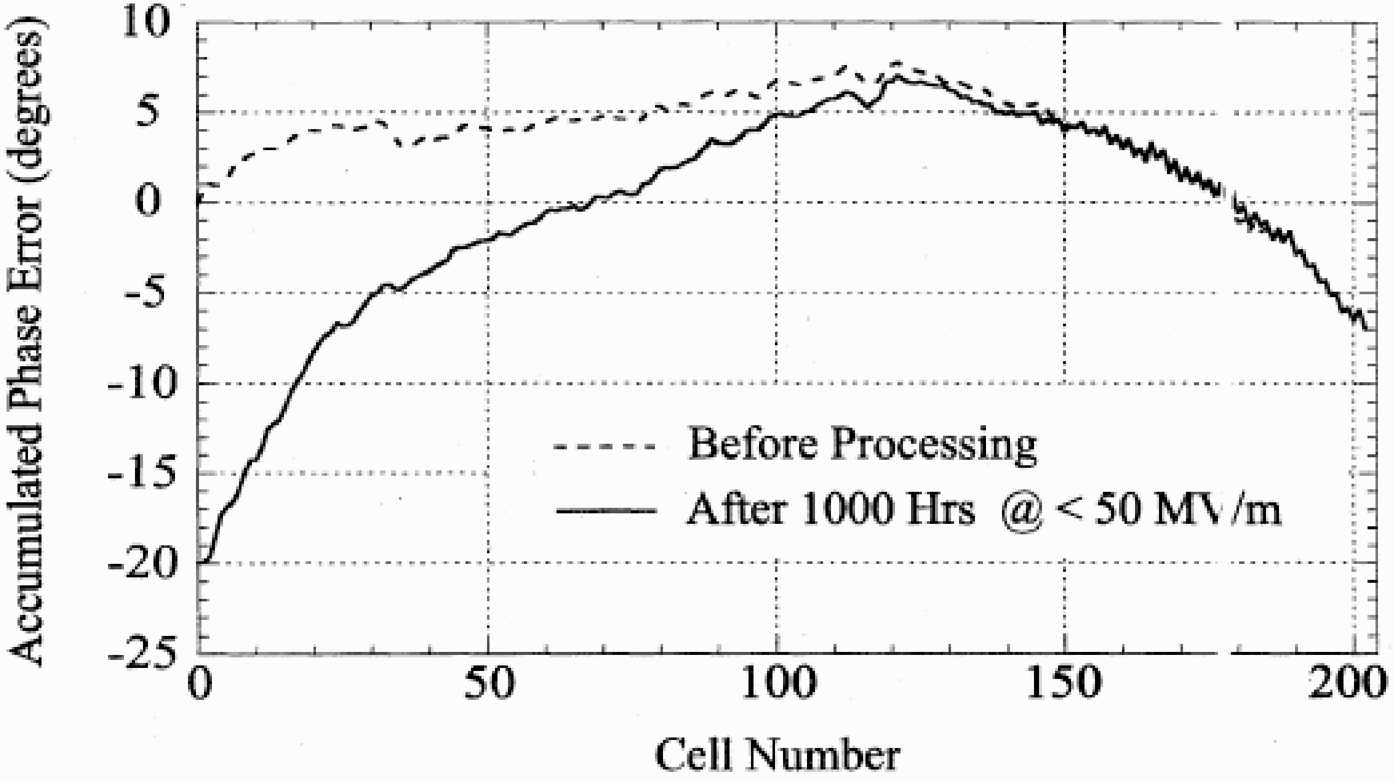


Figure 1.5: Operational Histories of Three Accelerator Structures as they are processed to high gradients. (a) A 1.8-meter-long NLCTA structure with group velocity 12% the speed of light at the input end. (b) A 0.5-meter-long test structure with group velocity 5% the speed of light at the input end. (c) A 1.0-meter-long test structure with group velocity 5% the speed of light at the input end. The data are unselected and correspond to a range of operational conditions.

Pitting on cell irises of a 1.8 m structure, after operation at G = 50 MV/m (max).



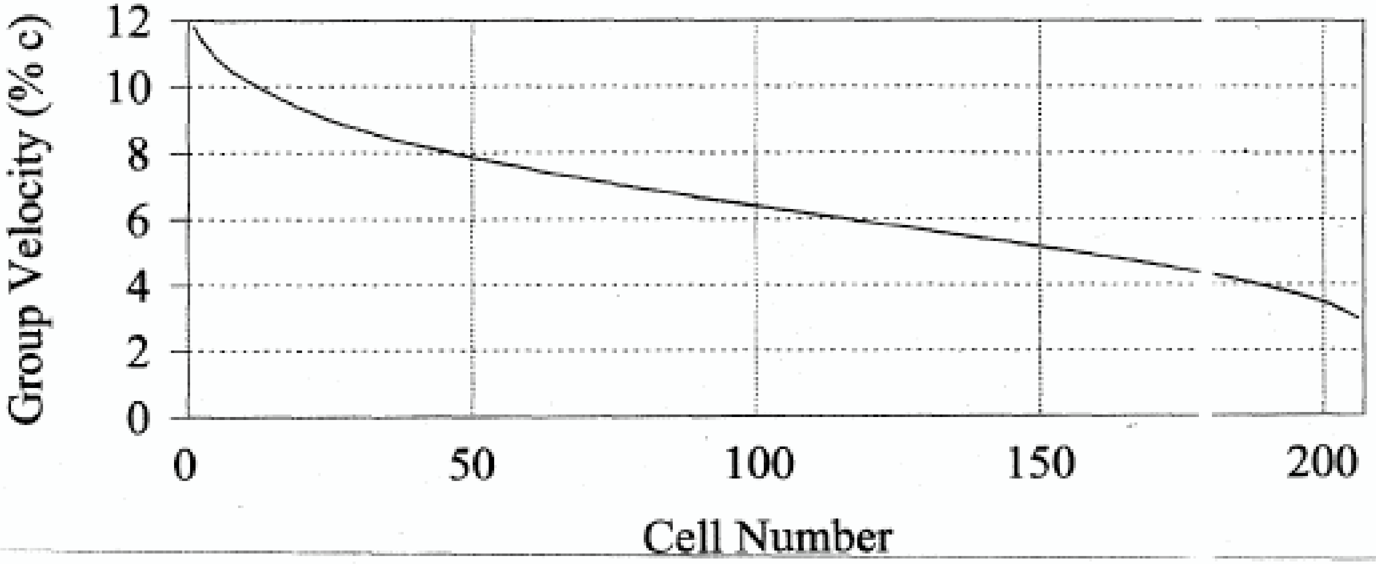
Breakdown Effect on Phase Advance per Cell



Why is Most Damage at the Upstream End ?

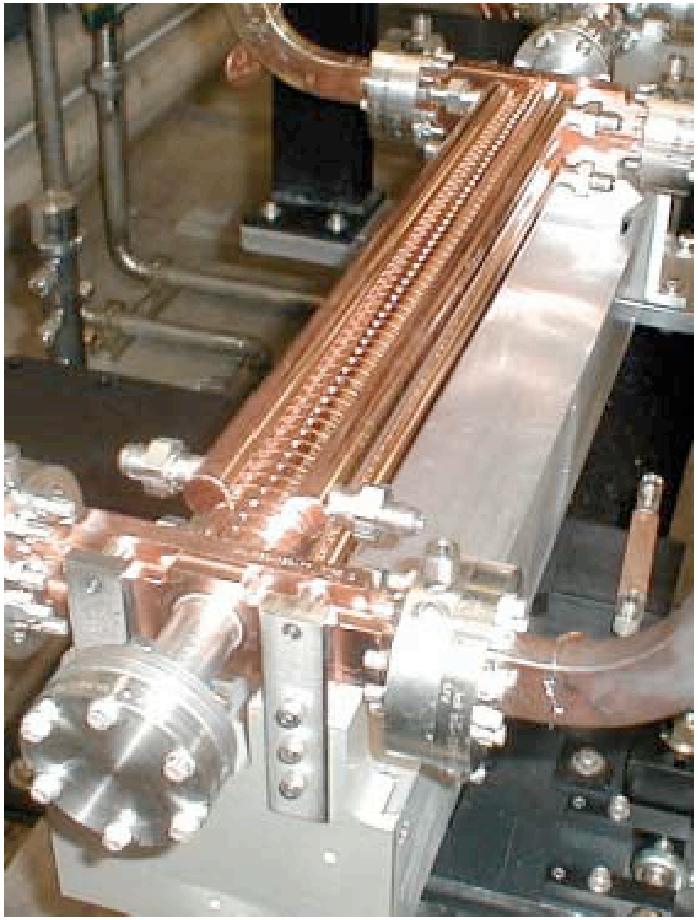
If Breakdown is Modeled as a Load Impedance,
Power Absorbed in the Load Scales as

Group Velocity^2 × Gradient^2



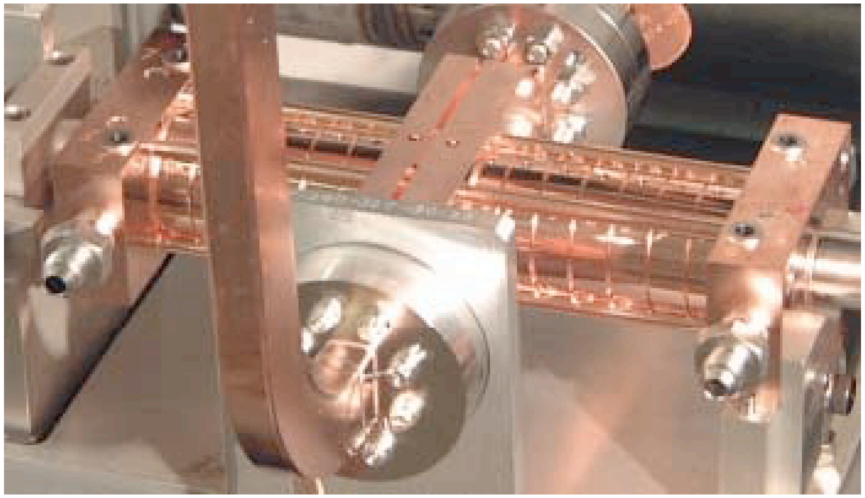
High Power Testing of Acc. Structures

NLCTA@SLAC (+KEK, FNAL)



Since 2000, test studies ongoing with both -

- Travelling wave strucs
- Standing wave strucs



Travelling wave struc.
"T53"-type (53cm, 60 cell)
Lower group vel. ~ 3 - 5 %c

Standing save struc.
"S20"-type
20cm, 15 cell, 124 ns field rise time

X-band Acc Structure Status

TW-Structures

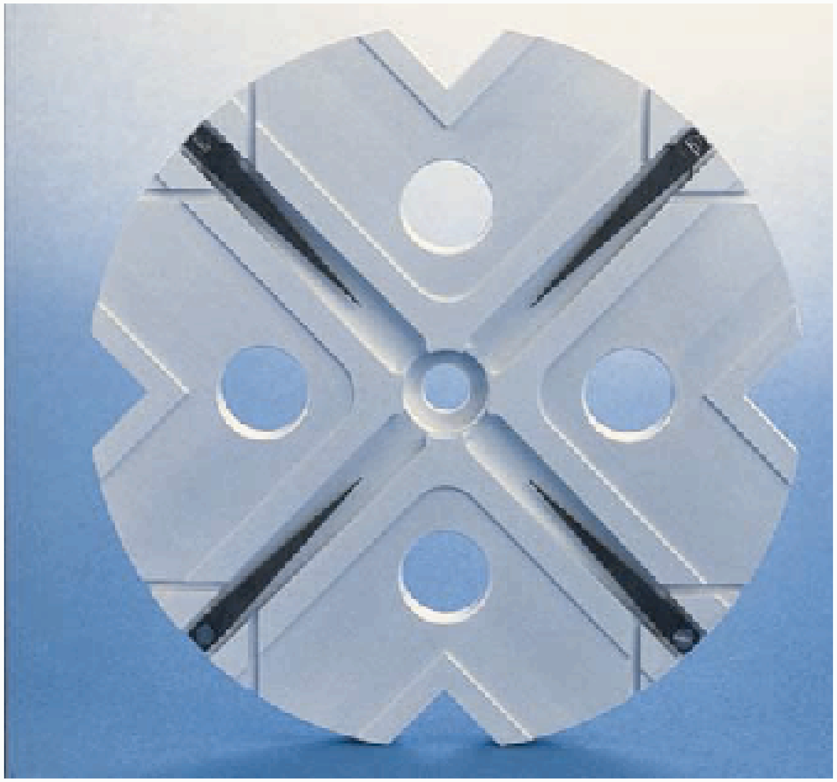
- Best results so far with 3%c struc., combined with new cleaning procedures
  - Breakdown 1 in 200K pulses at 70MV/m,
    after processed up to 86 MV/m
  - Breakdown 1 in 2000K pulses if run at 65 MV/m.
    This performance considered acceptable at NLC/JLC.
  - Damage level (0.5 deg phase shift) considered acceptable.
- Concentration of "hot spots" near/at input and output couplers seen
  - New coupler designs
  - Elliptical iris shapes for cells near the couplers
  - Testing in progress. More tests in 2002.
- Re-introduction of wakefied damping
  - Design work to re-accelerate in 2002.

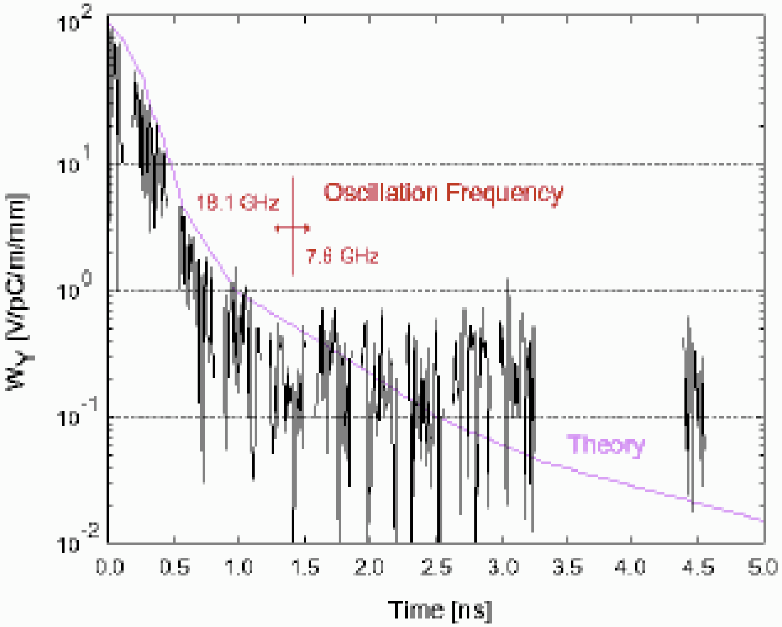
Linear colliders: R&D on 30 GHz warm rf

- Voltage breakdown limits-the baseline TDS 30 GHz CLIC structures have also shown evidence of breakdown damage, at peak surface fields of 300 MV/m.
- In this case, the evidence is that the breakdown is only dependent on the local peak surface field.
- In an interesting experiment cited by I. Wilson at LC’02, the peak surface field attainable was found to be 300-400 MV/m, **independent of frequency**, in the range 19-39 GHz, for pulses longer than about 10 ns.
- Slides following from talks by H. Braun at LC’02.

TDS design and modeling

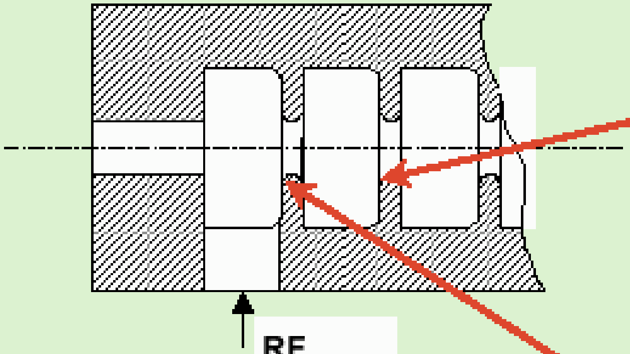
- Strong damping, moderate detuning
- Damping computed via double-band circuit model. Circuit elements determined from MAFIA frequency-domain calculations. Load modeled using HFSS.

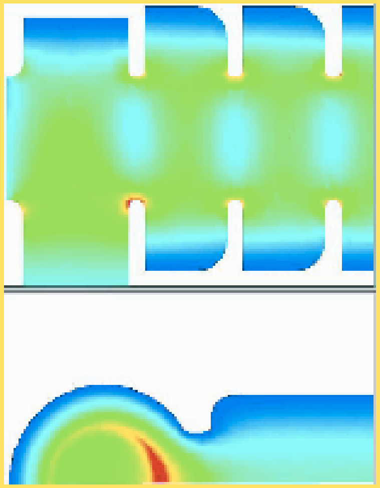


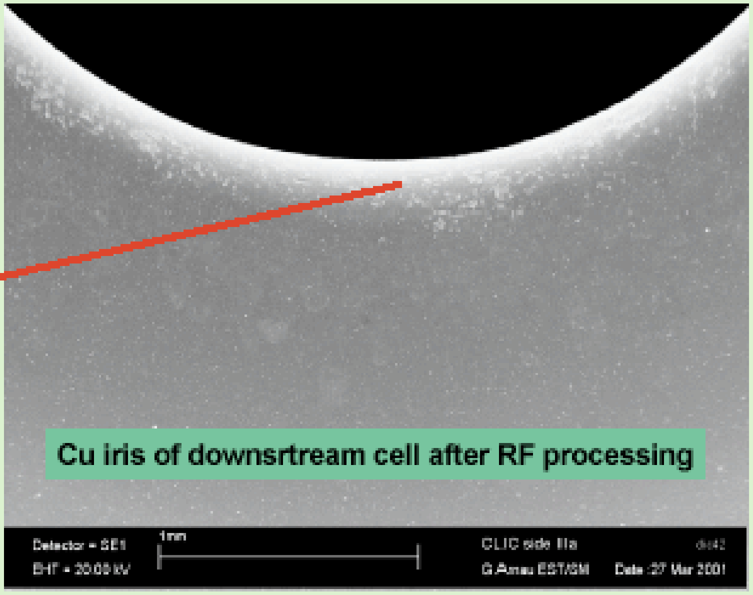


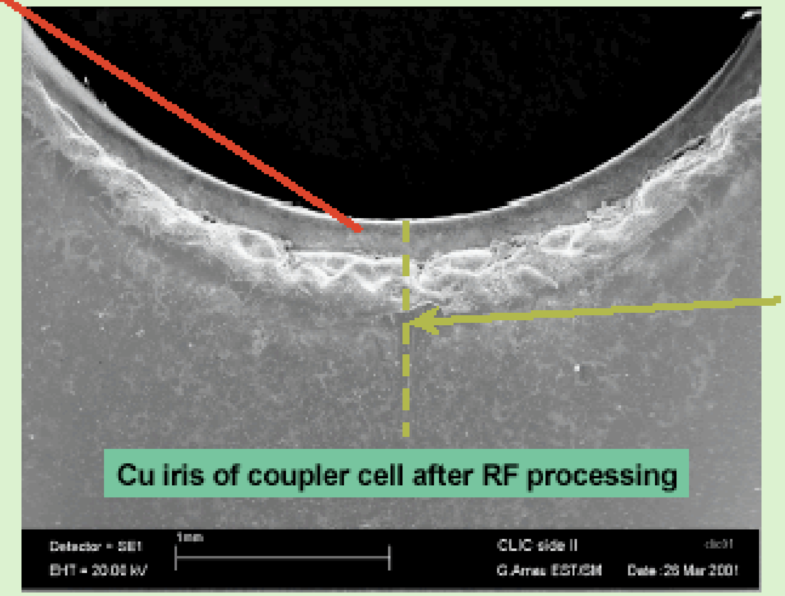
ASSET demonstration of damping

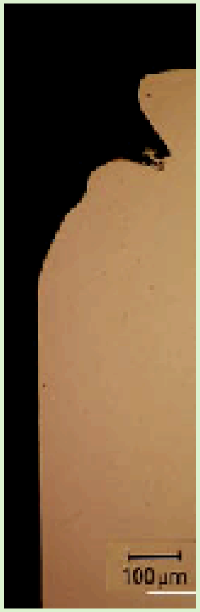
Observation of acceleration structure damage




HFSS simulation of E-field amplitude


Cu iris of downsrtream cell after RF processing


Cu iris of coupler cell after RF processing

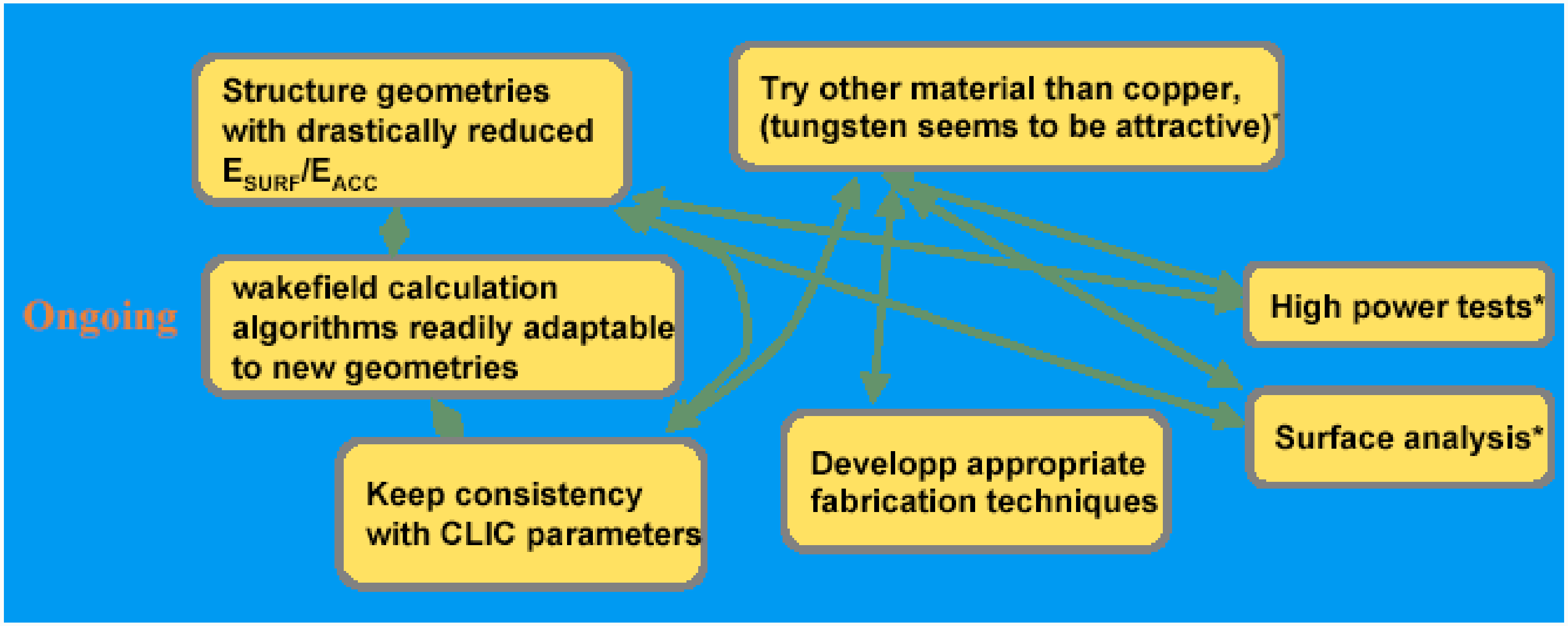


Starting point

Experimental results indicate:

- damage seems mainly correlated with peak $E_{SURF,}$ problems start at ◷ 300MV/m
- vacuum conditions & surface finish seems to have little effect
- CLIC TDS with old parameters can apparently not cope with 150 MV/m gradient

Ongoing



Structure geometries with drastically reduced E_{SURF}/E_{ACC}

Try other material than copper, (tungsten seems to be attractive)*

wakefield calculation algorithms readily adaptable to new geometries

High power tests*

Surface analysis*

Keep consistency with CLIC parameters

Developp appropriate fabrication techniques

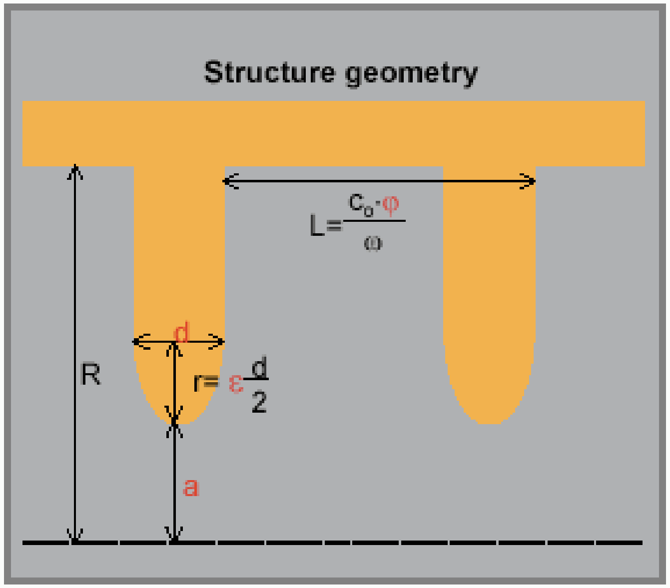
Goal

Accelerating structure capable of 150MV/m average acceleration without damage and consistent with CLIC parameters

*Ian's talk in WG2/Session 5

Cell geometries under considerations for reduced surface *E* field

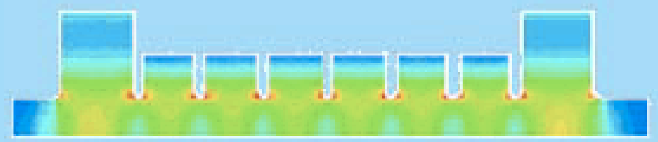
	CLIC/old	variant A	variant B
phase advance φ	$2\pi/3$	$2\pi/3$	$\pi/2$
a (mm)	2	1.75	2
d (mm)	0.55	1.0	1.0
ε	1	1.8	1.8
E_{SURF}/E_{ACC}	2.7	2.0	1.9
Q	4220	3940	2960
R_{SHUNT} (MΩ/m)	112	116	73
v_G/c	0.082	0.047	0.074
$P_{@\,150MV/m}$ (MW)	112	58	108



Comparison of mode launcher / old coupler design

Structure with resonant symmetric coupler

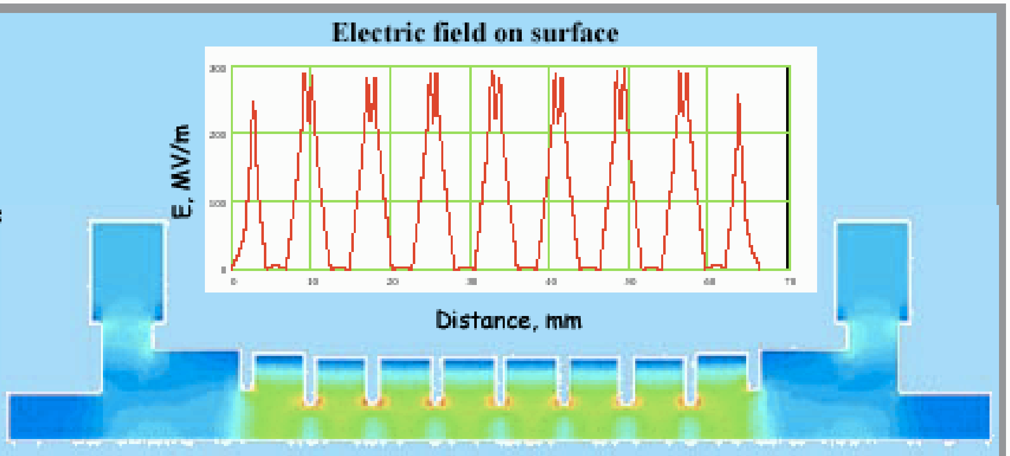
- Highest field strength in coupler cell



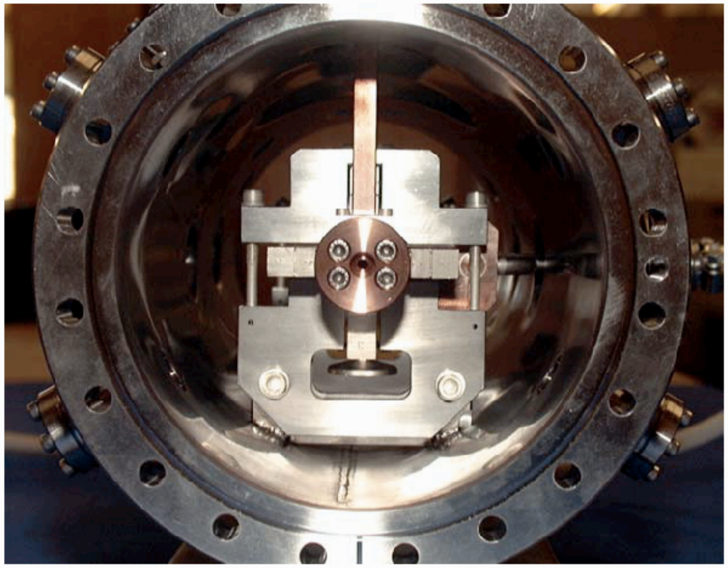
Structure with mode launcher

+ Field strength in coupler region nowhere exceeds field strength of regular cells

- Coupling region significantly longer

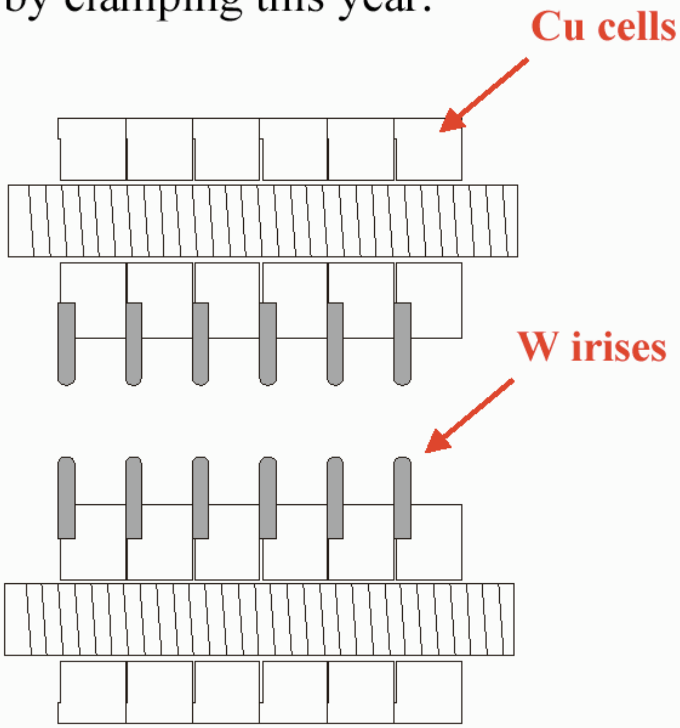


Tungsten Irises & Clamping



Worked very well in iris tests in CTF2 last year.

We plan to assemble entire structures by clamping this year.



How can clamping possibly work? What constitutes a good contact?

- Mostly microscopic surface area.
- Some role of oxide layers.

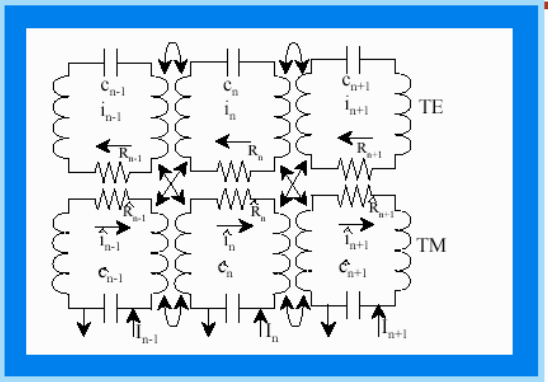
Best achieved when clamping by using a hard /soft material combination – like W and Cu.

Achieved when bonding diamond machined Cu surfaces and by using braze in a joint.

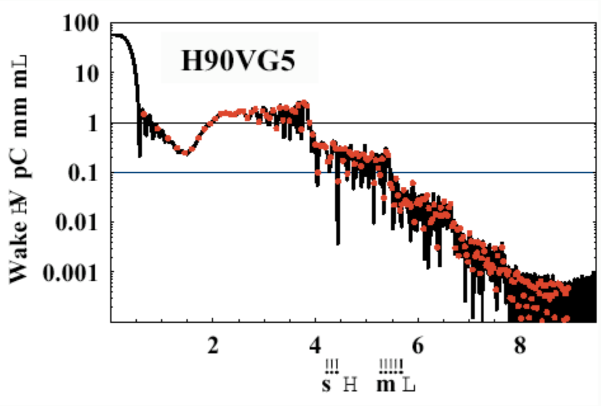
Linear colliders: R&D on warm rf-wakefields

- Structure wakefield management

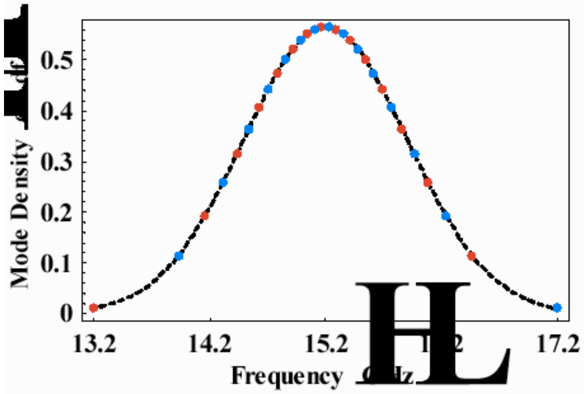
1. High Phase Advance Accelerating Structures



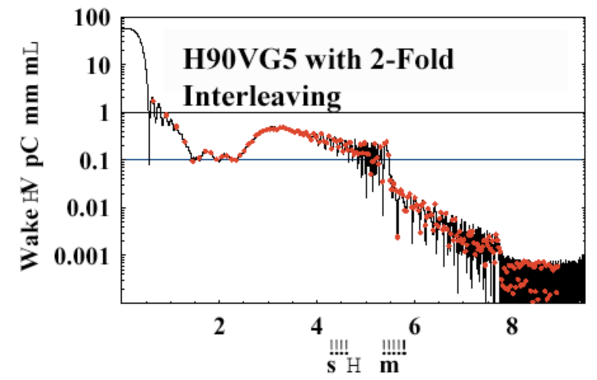
Circuit model for locally damped structure illustrating 3 cells of an n-cell chain



- Wakefield for single high phase (5π/6) advance structure: H90VG5 with moderate loading (Q ~ 1000).
- This structure is 90cm long.
- The initial group velocity is 0.0506c.



2-Fold interleaving of cell frequencies



- Wakefield from a single structure is clearly insufficiently damped.
- The frequencies of adjacent structures are interleaved

Wire measurements of structure impedance-an alterntaive to ASSET?

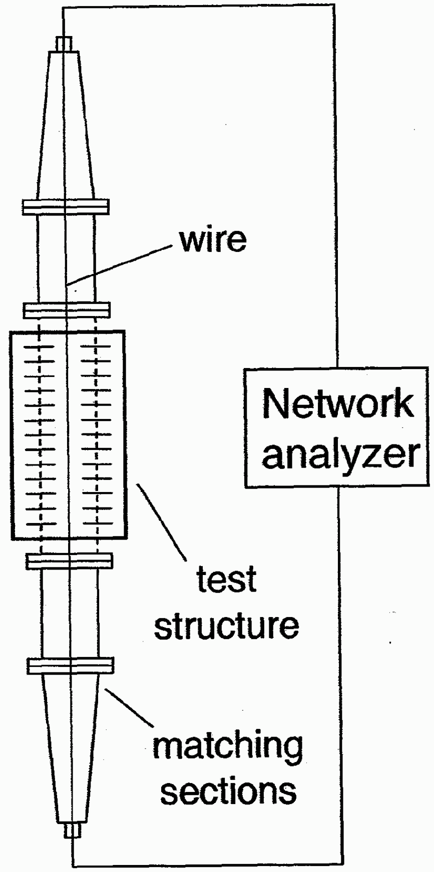
Principle

- proposed by Sands and Rees
- Measure wake field by help of wire passing through structure to be measured
    - time domain ⇒ wake field
    - frequency domain ⇒ modes

- Measure mode properties by measuring S21,

- $k_{loss} = 2\pi Z_0(\Delta f)_{1/2}(1-S_{21})$

(P. Wilson;
R.L.Gluckstern)



Linear colliders: R&D on power delivery components

- Summary/comparison slides fromY. H. Chin (KEK) at LC’02

Y.H. CHIN
LC 2002

Klystron Summary

	JLC-X	NLC	TESLA
Type:	11.424GHz PPM	11.424GHz PPM	1.3GHz Solenoid-MBK
Goals:	75MW, 1.5μs >55% eff.	75MW, 3.2μs >55%	10MW, 1.5ms 70%
Best Scores: So Far	74MW, 1.4μs 54%~56% (PPM-2)	76MW, 28μs 58% (XP3-1)	10MW, 1.5ms 65% (THALES TH 1801)
Next to Come:	PPM-3 for 60% eff.	XP3-2 by CPI	Hor. version ↓ Nov. 2002 CPI VKL8301 ↓ end 2002 – beginning 2003
Delivery Date:	Just Arrived	This Spring	Nov. 2002 end 2002 – beginning 2003 and more TH 1801

Conclusions:

1. There have been good progresses in the last two years over the world.
2. The maturity of X-band PPM klystron technology is just around the corner.
3. All klystron R&Ds are on the right track.
4. People are working hard to refine the RF and mechanical designs, and the above klystrons are their main-stream ones.

1 At NLC, there are concerns about the klystrm lifetime (goal ~50k hrs)

- The most likely cause of klystron death is the cathode arcing due to Barium deposition on anode surface (S. Gold)

2. At JLC, they are looking for a way to doube the RF power from a klystrm (150MW) to redece the number of the klystrm to a half.

R&D also in progress:

JLC-X	NLC	TESLA
150MW MBK at 1.5μs	75MW or 150MW Sheet-Beam Klystron	Already adopted MBK at TH1801

Y.H.Chin
LC2002

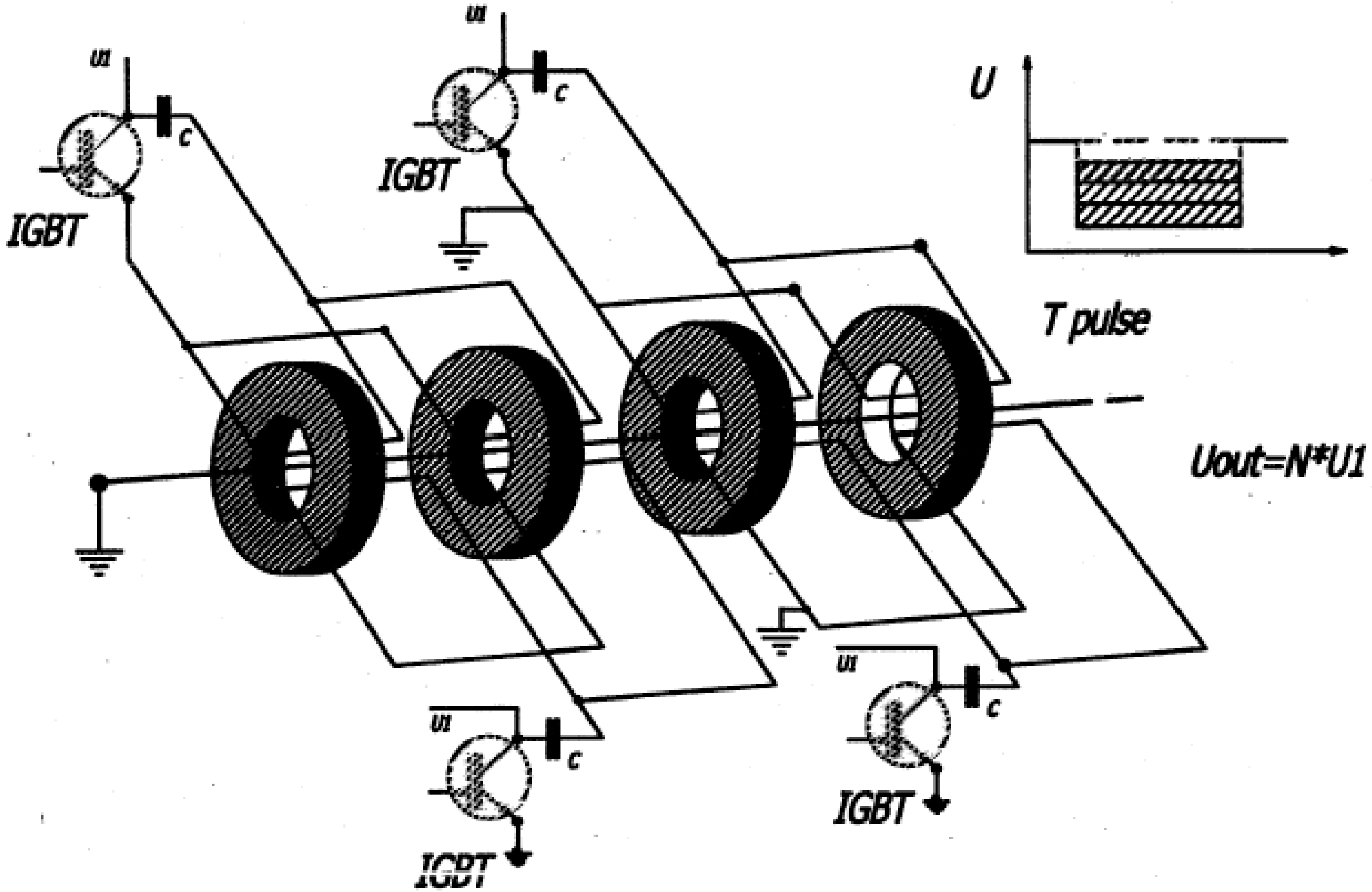
Modulator Summary

	JLC-X	NLC	TESLA
Type:	Solid-State (IGBT) Linear Induction	Solid-State (IGBT) 3-Turn Induction	Solid-State (IGCT) Bouncer
Goals:	8-pack, 500kV, 260×8A 2μs >80% eff. 100∼150 Hz	8-pack 500kV, 250×8A 3.2μs, >80% 120 Hz	1-pack 115kV, 130A 1.5ms, >85% 5∼10 Hz
Best Score So Far:	Still in design	3∼2.5μs 400∼500kV 450∼650 A ↙ ↘ Water S-band >80% eff. at 4-Pog	120kV, ∼80A 1.5ms 85% eff. 5Hz
Next to Come:	4-pack	8-pack for NLCTA	Just more
Delivery Date:	by mid 2003	by mid FY 2003	soon

Conclusions:

1. All modulators are solid-state switch type for longer lifetim
2. More than 80% efficiency was proven to be possible.
3. R&Ds are on the right track.
4. More failure tests need to be done for protection ab

Linear Induction type Modulator Concept



V.Vogel, BINP-KEK, 2002

Pulse Distribution System Summary

LC2002

	JLC-X	NLC	TESLA	CLIC
Type:	Single-mode DLDS for 4 RF clusters (6 str.)	Dual-mode DLDS for 8 RF clusters (6 str.)	No compression for 3 Cryomodules (12 9-cell cav.)	Drive beam
Goals:	600MW, 1.5μs >85% eff.	600MW, 3.2μs >85%	10MW, 1.4ms >85%	
Status:	Low & high power testing in progress		In operation at TTF 2	
Next to Come:	High power testing at 150 ~ 300MW at J-LUFT	High power testing at 600MW at 8-pack phase-I and II		
Date:	2002~2004	2002~2004		

Conclusions:

1. Hardware wise, the pulse distribution system at JLC/NL has the slowest progress in high-power testing among other RF components.

2. However, this is the most active part from the theoretic point view, and alot of progresses have been made for the quest of more efficient and compact

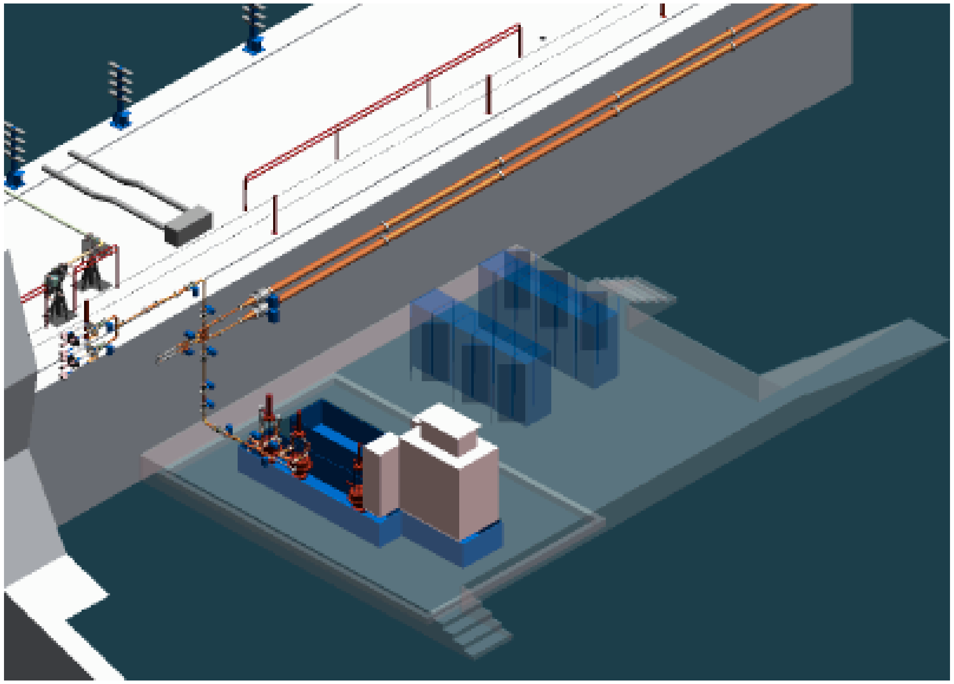
Linear colliders- R&D on warm rf- X-band power delivery systems

- “8-pack” project is the X-band “string test”

The 8-Pack Project at NLCTA

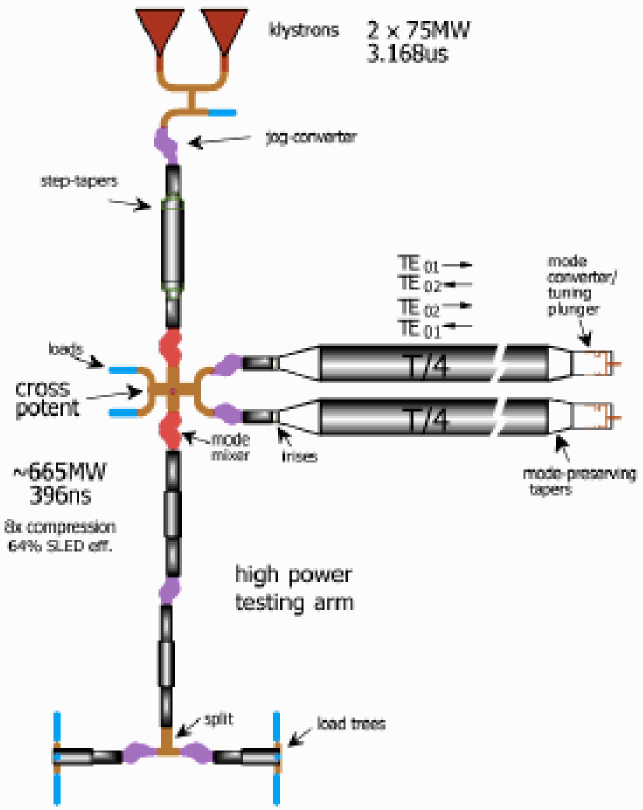
An update of the status and schedule for the project.

- Modulator and klystrons turn on 6/11
- Install SLED in October
- High power operations Jan., 2003



Goals – Phase 1

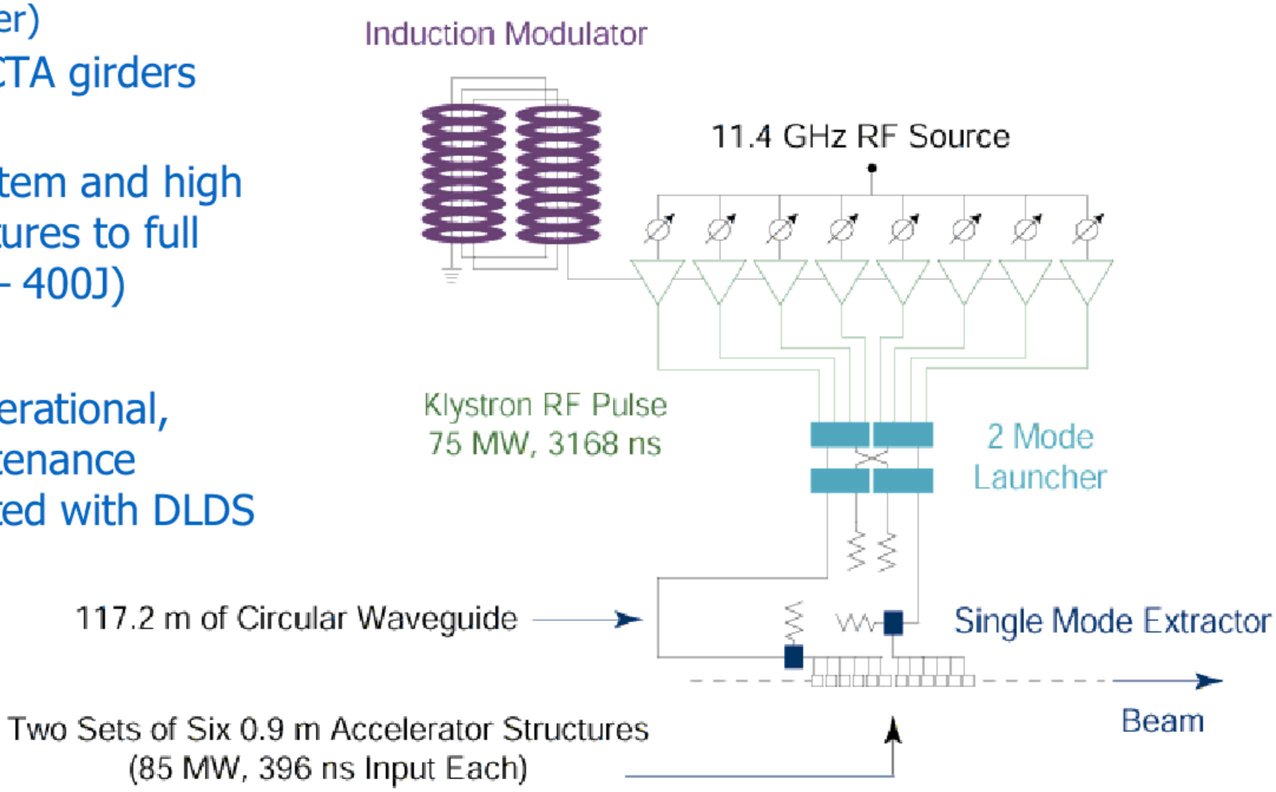
- Demonstrate SLED II pulse compression on 2 tubes to attain >600 MW, 400 ns (@ cross potent) – meeting the NLC spec.
- Set up a station for high power tests of DLDS components & begin testing components
- Establish a station for 75 MW klystron operation



Multi-Moded SLED-II

Goals – Phase 2

- Demonstrate DLDS pulse compression to attain NLC power specs.
  - 500 MW, 396 ns
    (@ girder)
  - Power NLCTA girders
- Test DLDS system and high gradient structures to full energy (200J – 400J)
- Investigate operational, stability, maintenance issues associated with DLDS



Induction Modulator

11.4 GHz RF Source

Klystron RF Pulse
75 MW, 3168 ns

2 Mode
Launcher

117.2 m of Circular Waveguide

Single Mode Extractor

Beam

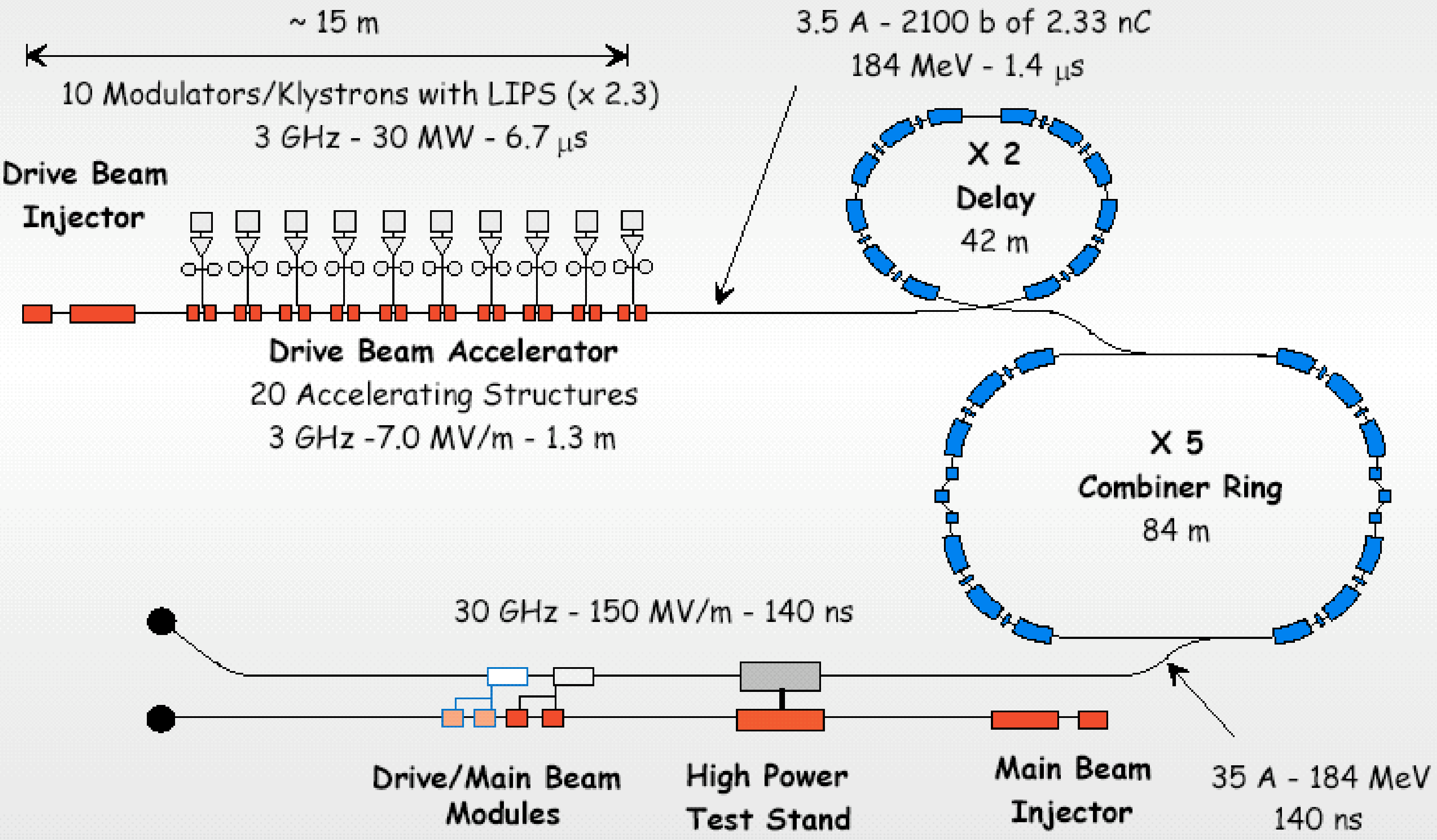
Two Sets of Six 0.9 m Accelerator Structures
(85 MW, 396 ns Input Each)

Linear colldiers- R&D on warm rf-CLIC power source

- CLIC power source development-CTF3 at CERN
- Issues:
  - BBU in the drive beam accelerator
  - Delay loop and combiner rings must be isochronous to prevent bunch lengthening-higher order terms in momemtum compaction limit acceptable momentum spread
  - CSR in the rings will increase energy spread, could cause bunch lengthening
  - Combiner Ring impedance control-to limit energy spread
  - Beam stability in the decelerator-energy spread reaches 100%

CTF3 conceptual lay-out

CTF3 - Test of Drive Beam Generation, Acceleration & RF Multiplication by a factor 10



~ 15 m

10 Modulators/Klystrons with LIPS (x 2.3)
3 GHz - 30 MW - 6.7 μs

Drive Beam Injector

3.5 A - 2100 b of 2.33 nC
184 MeV - 1.4 μs

X 2
Delay
42 m

Drive Beam Accelerator
20 Accelerating Structures
3 GHz -7.0 MV/m - 1.3 m

X 5
Combiner Ring
84 m

30 GHz - 150 MV/m - 140 ns

Drive/Main Beam Modules

High Power Test Stand

Main Beam Injector

35 A - 184 MeV
140 ns

R.Corsini

Linear collider:Main linacs Potential R&D items: beam dynamics

- Instrumentation and diagnostic development
- Simulations:
  - Tuning algorithms to suppress correlated energy spread
  - Full system simulation development, including simulations of start-up of machine
  - Coherent synchrotron radiation in bunch compressors
  - Dark current transport; effect on diagnostics
- Studies of vibration suppression systems
- Feedback system development
- Pre-linac collimation system design

Linear colliders: main linacs R&D

- Diagnostic systems-
  - BPM’s: quadrupole and structure
  - Emittance measurement-laser wire; laser interferometer (scattering from fringes)

Slides following from Steve Smith (SLAC), Y. Honda (KEK), LC’02

NLC Linac BPMs

- “Quad” BPM (QBPM)
  - In every quadrupole (Quantity ~3000)
  - Function: align quads to straight line
  - Measures average position of bunch train
  - Resolution required: 300 nm rms in a single shot
- Structure Position Monitor (SPM)
  - Measure phase and amplitude of HOMs in accelerating cavities
  - Minimize transverse wakefields
  - Align each RF structure to the beam
  - 22 k devices in two linacs
- “Multi-Bunch” BPM (MBBPM)
  - Measure bunch-to-bunch transverse displacement
  - Compensate residual wakefields
  - Measure every bunch, 1.4 ns apart
  - Requires high bandwidth (300 MHz), high resolution (300 nm)
  - Line up entire bunch train by steering, compensating kickers

QBPM Requirements

Parameter	Value	Conditions
Resolution	300 nm rms	@ 10^{10} e^- single bunch
Position Stability	1 μm	over 24 hours **(!)**
Position Accuracy	200 μm	With respect to the quad magnetic center
Position Dynamic Range	±2 mm	
Charge Dynamic Range	5×10^8 to 1.5×10^{10} e^- per bunch	
Number of bunches	1 - 190	
Bunch spacing	1.4 ns	

Develop Cavity BPM Prototype

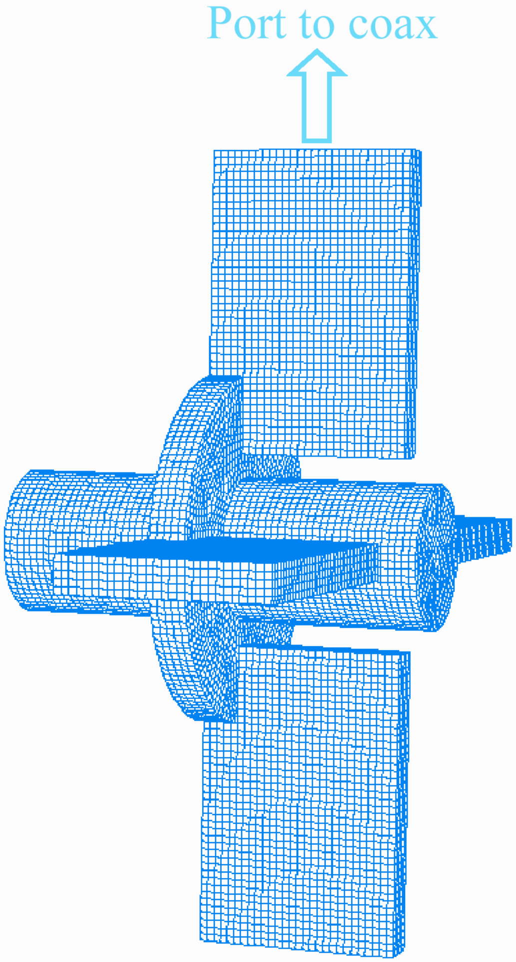
- Team:
  - Ron Johnson, Zenghai Li, Takashi Naito, Jeff Rifkin, S. Smith
- Frequency: 11.424 GHz
- Axially symmetric X-Y cavity
- TM_{110} mode couplers designed by Z. Li
- Two coupler per mode for prototype cavity
- Integrate fundamental mode phase reference cavity in same block.
- Measure on bench
- In beam

BPM Cavity with TM_{110} Couplers

- Dipole frequency: 11.424 GHz
- Dipole mode: TM11
- Coupling to waveguide: magnetic
- Beam x-offset couple to “y” port

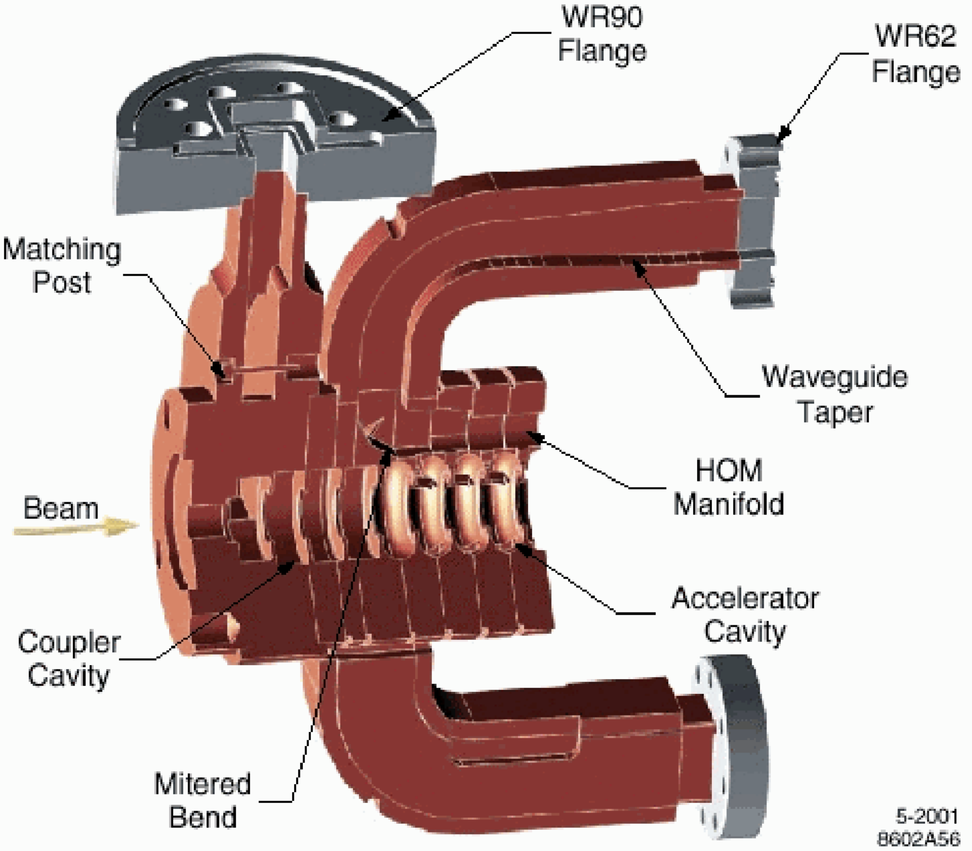
- Sensitivity: 1.6mV/nC/μm
  (1.6×10^9V/C/mm)

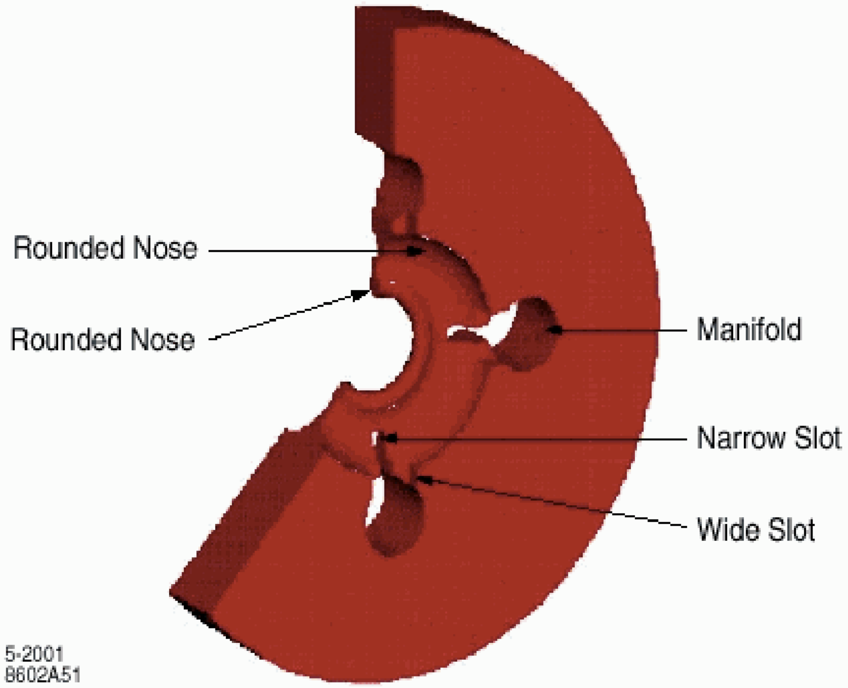
- Couple to dipole (TM11) only
- Does not couple to TM01
  - May need to damp TM01
  - OR, use stainless steel to lower Q
- Compact
- Low wakefield



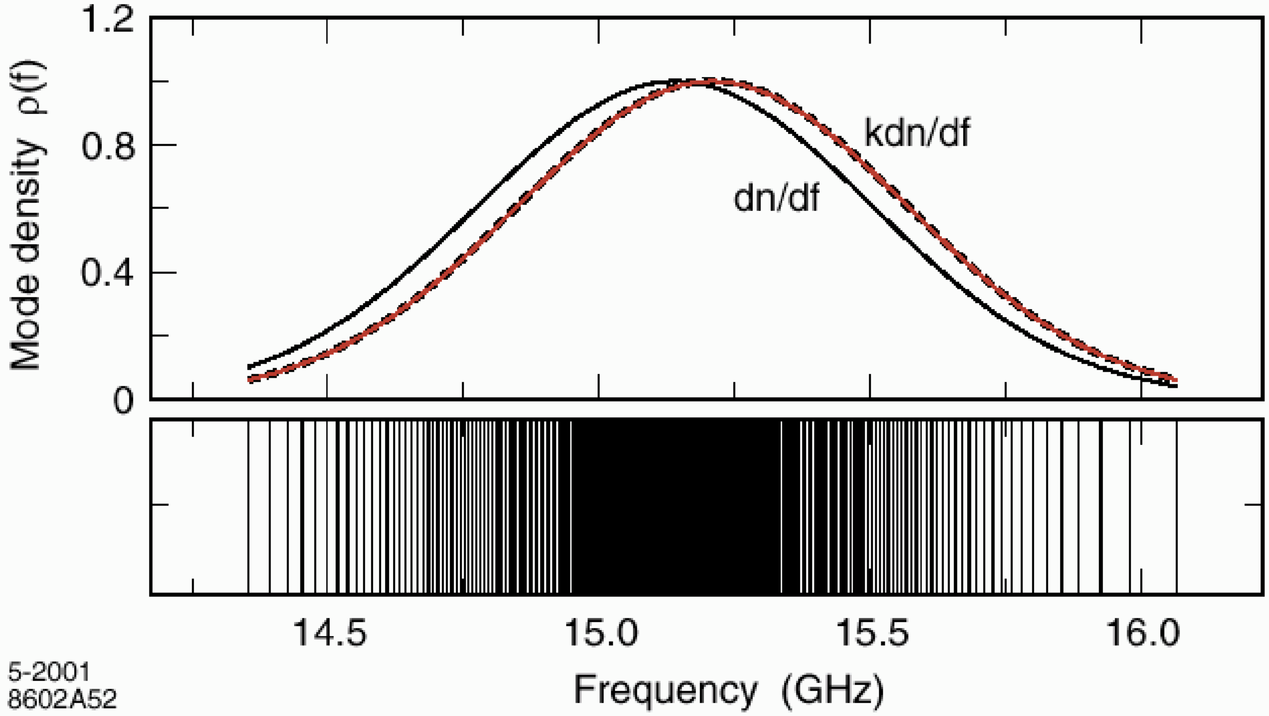
Structure Position Monitor

- Use dipole modes in accelerating cavities to measure beam position.
- Align each RF structure to the beam
- Minimize transverse wakefields





Transverse Modes in Structure



RDDS1 dipole mode frequency distributions: dn/d*f* is the mode density and *k*dn/d*f* is the density weighted by the mode kick factors (*k*).

- Transverse modes contain position information
- Modes associated with z position along structure.
- Tunable receiver can measure position along structure.

SPM Requirements

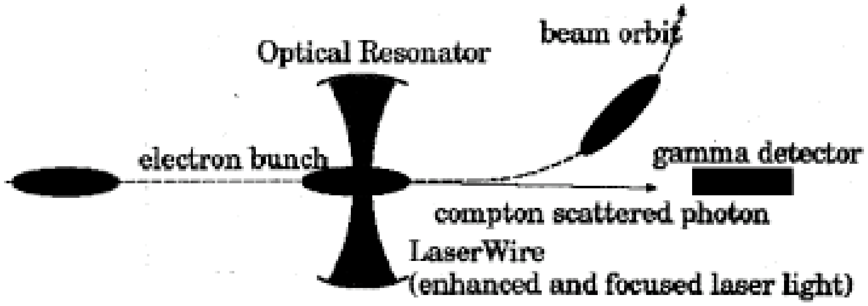
Parameter	Requirement	Comments
Quantity	~22,000 X,Y BPM's ~ 700 X,Y BPM's	in X-band linacs in S-band linacs
Resolution	rms = 5 μm or 10% of beam position, whichever is greater	single bunch of 3×10^9 e^-, for at least one mode near each end
Position Dynamic Range	R < 3 mm R < 0.5 mm	single bunch or low current multibunch full current, multibunch
Stability of Center	<1 μm over 30 minutes	
Survival	90 bunches @ 1.5×10^{10} at 3 mm radius	Must not damage receiver

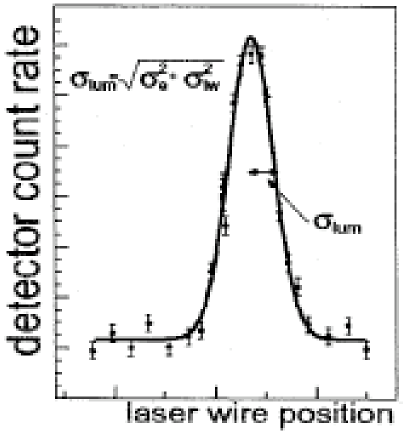
Structure Position Monitor

- Looks promising
- Have not developed even prototype electronics
- R&D needed on integrated RF module
- Large system, it must be:
  - high performance
  - reliable
  - cheap

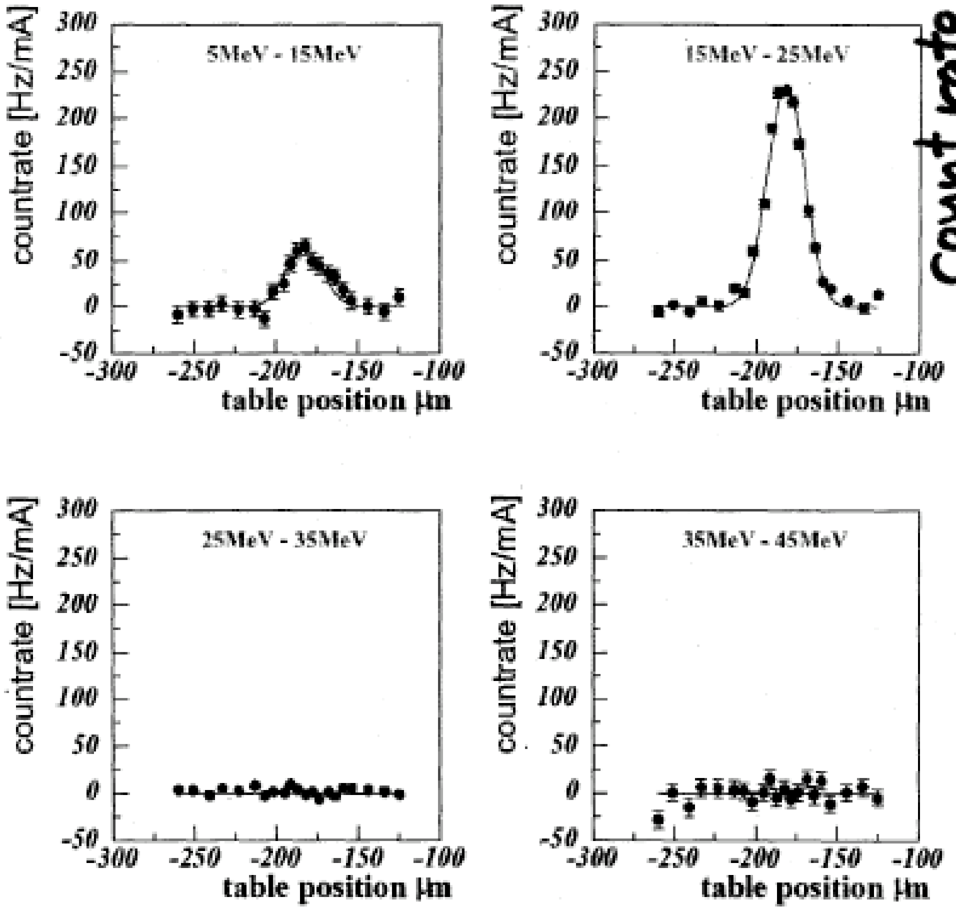
■Laser wire monitor (principle)

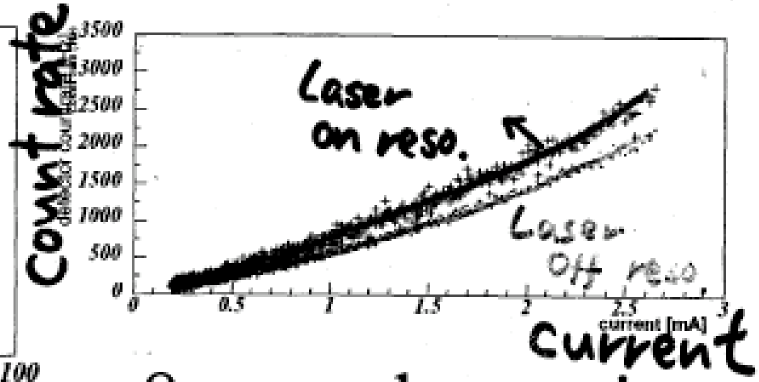
- use thin laser light (laserwire) as a target
- detect compton scattered gamma ray
- scan laserwire position measuring gamma ray yield





■last year measurement





- 8 μ m e-beam size measured
- laser waist size 7.25±0.08 μ m
- effective laser power 11W

↑

NOT ENOUGH

■Requirement

- laser waist size < e-beam size
  - typical e-beam size in ATF DR
    - horizontal: 100 micron
    - vertical: 10 micron
  - laser waist size must be measured

$$\sigma_{measured} = \sqrt{\sigma_e^2 + \sigma_{laser}^2}$$

- high laser power for good S/N
  - background gamma ray (kHz)
  - laser power > 100W

◆ Optical cavity to realize thin and intense laser beam

Laser interferometer-Compton scattering from the fringes

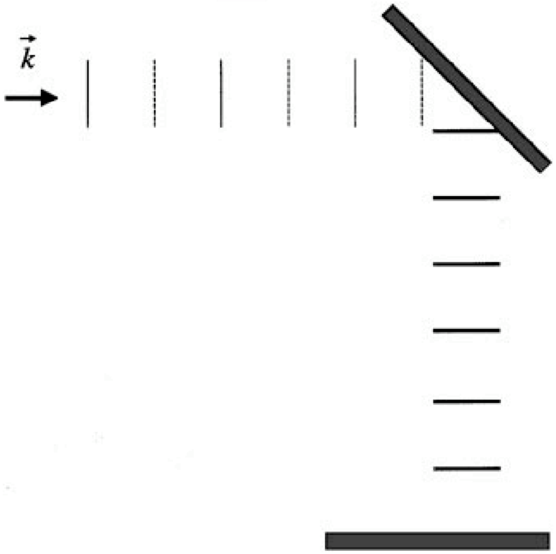


Figure 12 Diagram of simple laser interferometer for beam size measurement. A laser with wave vector $\vec{k}$ is introduced into a resonant cavity. The resulting standing-wave pattern has intensity maxima (dark solid lines) whose spacing is half the wavelength of the incoming laser (solid lines, maxima; dashed lines, minima).

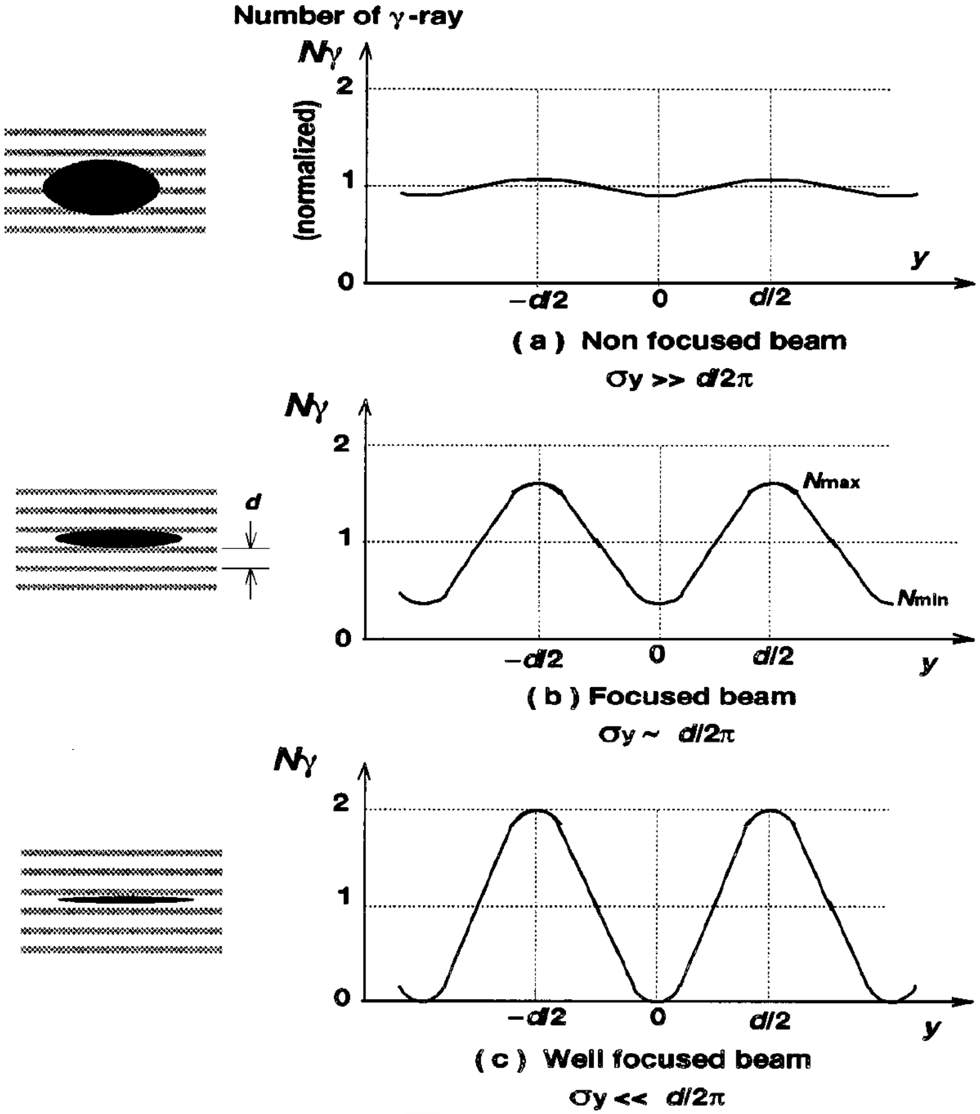


Figure 14 Use of laser-interferometer to measure a beam size. A beam that is large relative to the fringe spacing does not produce modulation in the intensity of Compton-scattered photons as it is scanned across the interference pattern (*top*); a beam that is very small relative to the fringe spacing produces nearly 100% modulation (*bottom*).

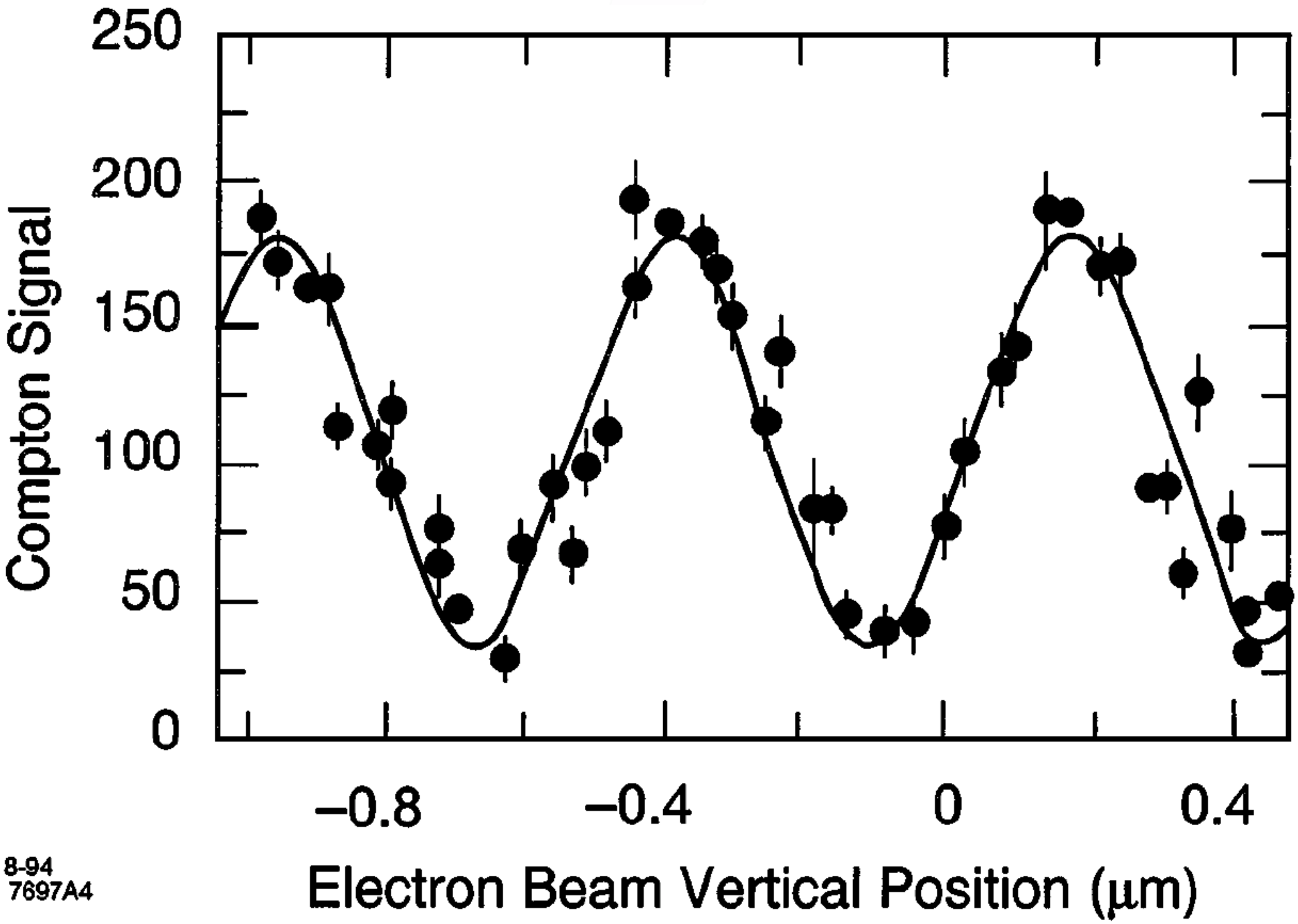


Figure 27 Vertical beam size measured with 174° mode. The modulation depth is 66%, corresponding to a beam size of 77 nm.

Potential R&D-Simulations

- Predicted luminosity performance of LC’s comes from simulations. Better get it right!
- End-to-end simulations (DR to IP, source to DR, …) are crucial and just starting to get done.
- Is all the relevant physics included in the simulations? We need benchmarking of simulations against each other and against real machines-some of this done with LIAR for SLC, but more is needed.
- Tests of practicality of tuning algorithms in realistic environment are needed, e.g., machine modeling from start-up.

The role of simulation codes

Test accelerators cannot test linac performance.

Predict linac performance based on simulation codes…

Programs used in the context of linear collider studies:

LIAR MAFIA TRANSPORT SAD MAD GUINEAPIG MERLIN TraFIC^4
MUSTAFA PLACET Q URMEL DIMAD GDFIDL LEGO WAKE TRACK
FFADA PARMELA FLUKA GEANT CAIN OMEGA3P TAU3P HFSS
PHI3P **+ many others (some nameless heroes)**

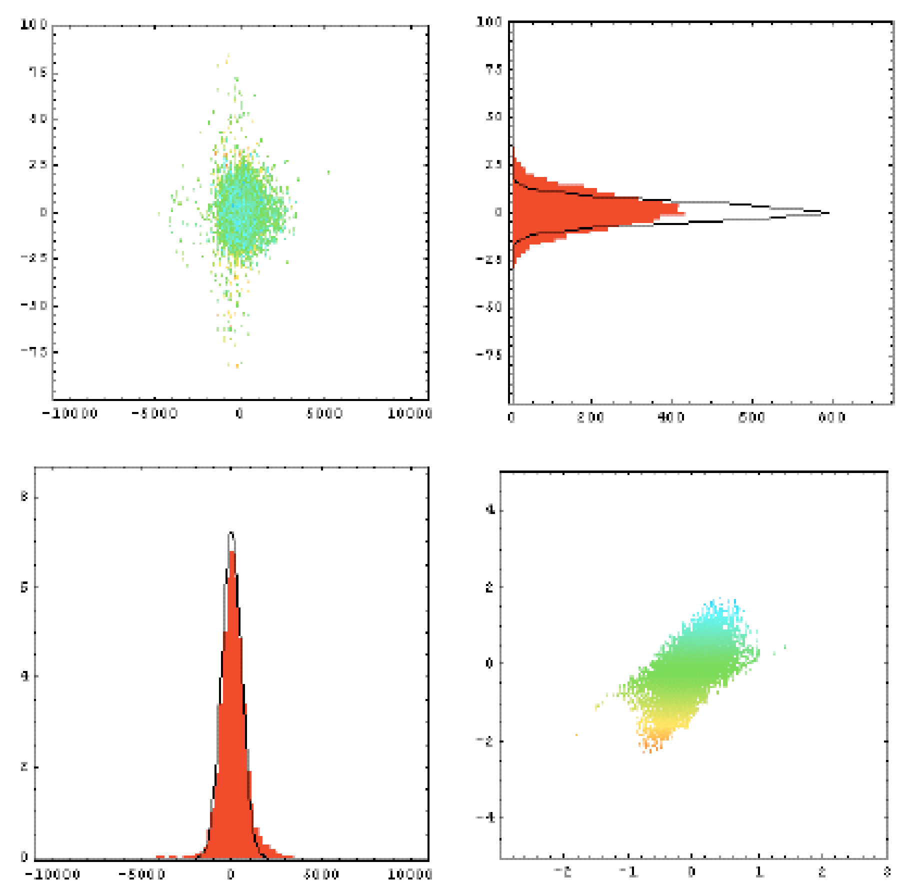
Computational activity for linear colliders is:

manifold and redundant

Especially: LIAR written for and tested against SLC linac
Incorporates lot of experience from SLC
Used for cross-checks of other programs (e.g. PLACET)

TESLA Examples: DR→IP

- X-Y scatter plots at IP
- Adjusting bunch compressor RF phase by ±2.5°



z-δ plot

Potential R&D-simulations

- Tracking of dark current electrons in accelerating cavities
  - Studies of breakdown
  - Captured electrons:
    - Effect on beam diagnostics
    - Tail and background generation

Tracking of tracks with random launch position and phase a=2mm r_a=0.3mm

Tracking of field emission electrons in CLIC cavities
(H. Braun, CERN, at LC'02)

Potential R&D

- Vibration suppression-example from Josef Frisch talk at LC’02

Technologies: Sensors

This is the limiting technology for inertial systems

First tests done with piezo-electric accelerometers.

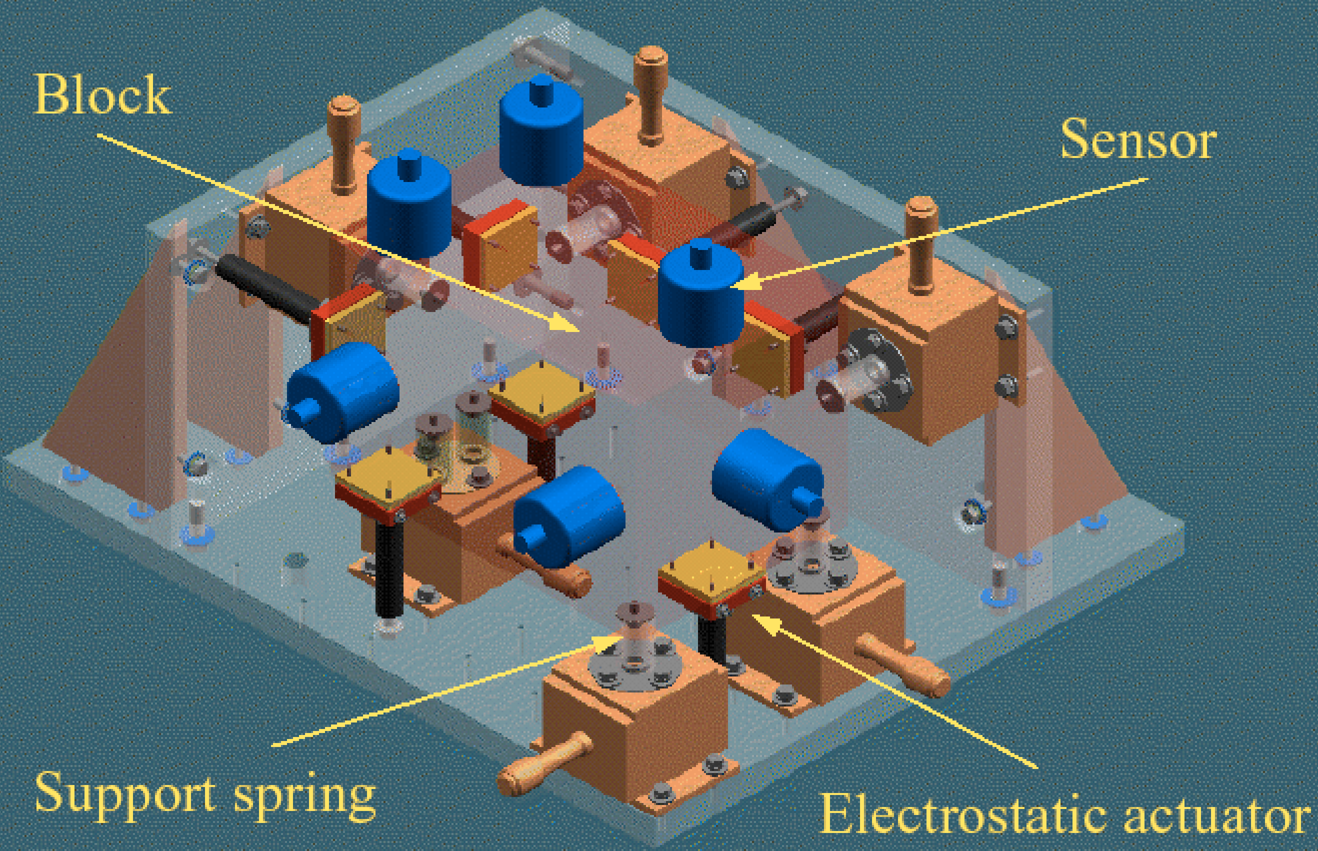
- Simple to use, response to (nearly) DC acceleration
- High noise floor: spec was ~10nm integrated noise at 1Hz, measurement was >10X worse than specification.

Now using compact geophones.

- Velocity sensitive: low frequency response is f^{-3}
- Noise above 1Hz is a few nanometers (measured).

Developing “mini-seismometer” with much lower noise (discussed later).

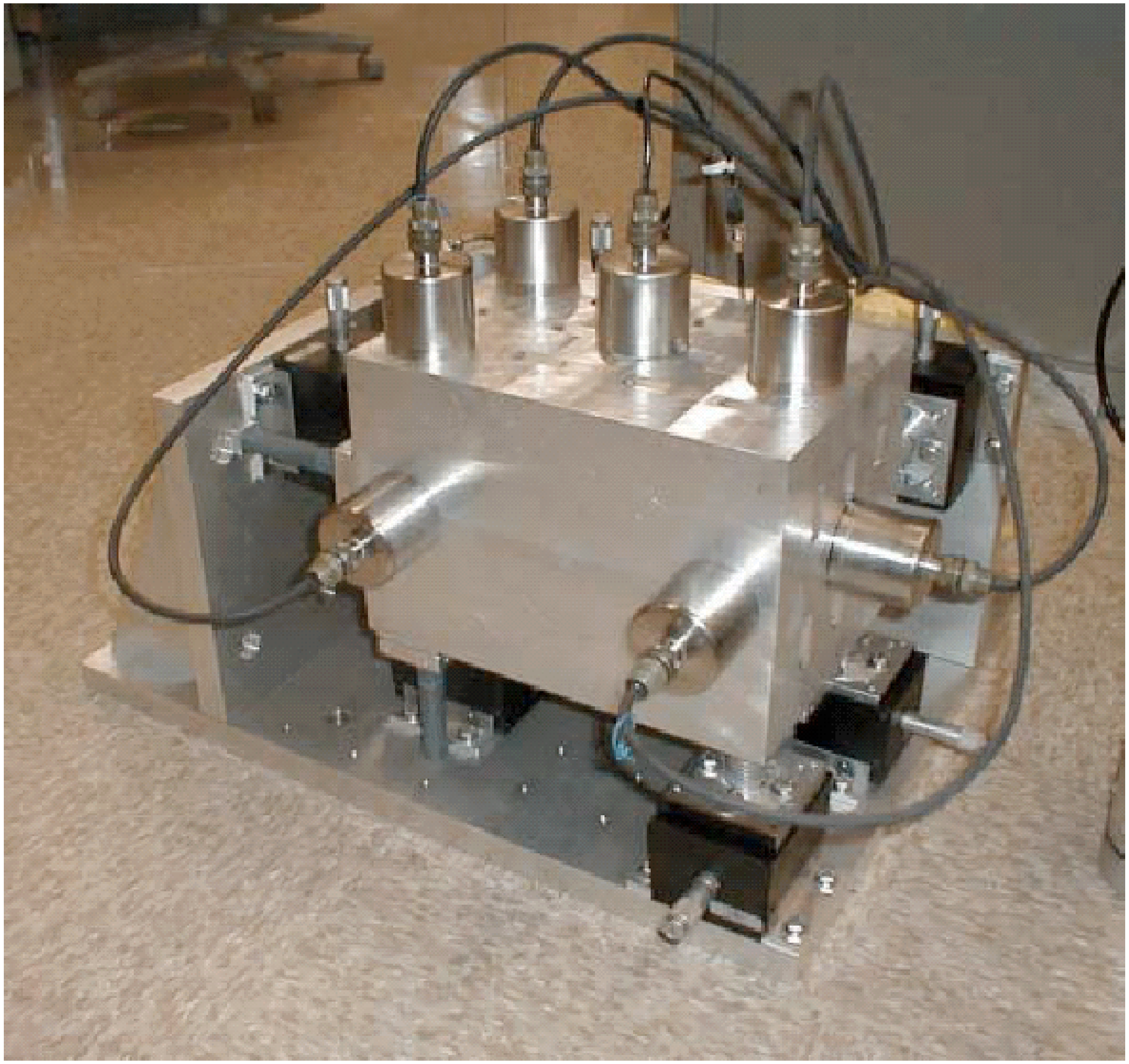
Test System



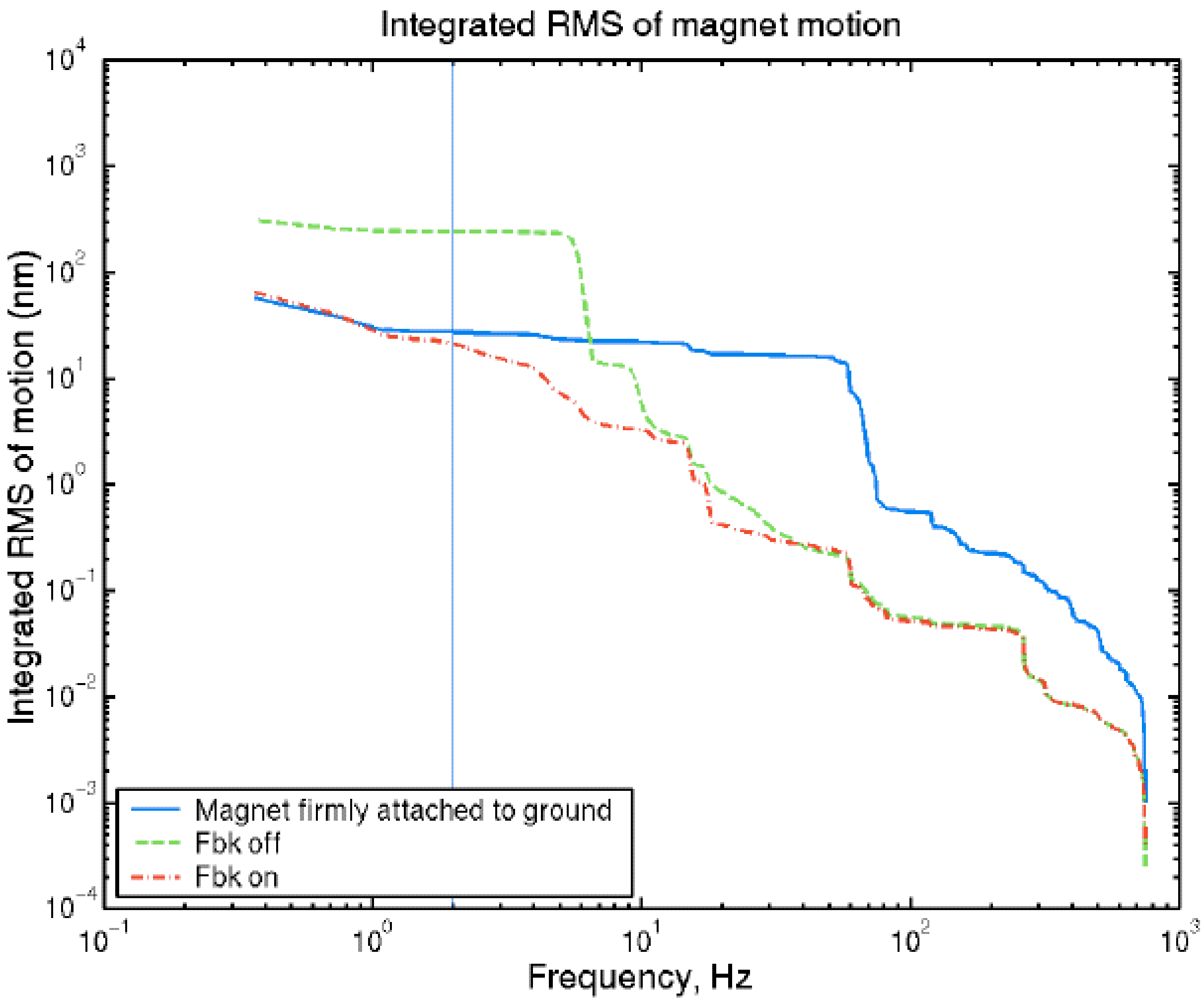
30Kg Block

Piezo-accelerometers shown.

Resonances:
3-10Hz



Effect of block suspension and feedback



Potential R&D

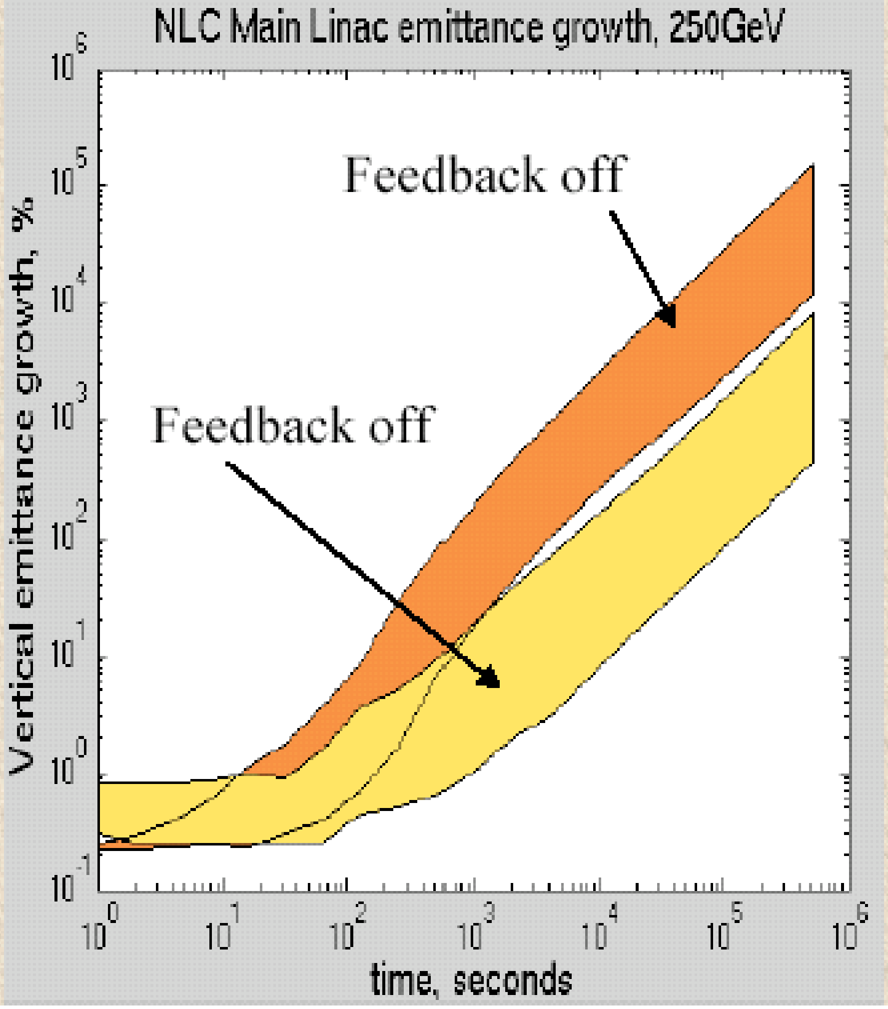
- Feedback-example from Tom Himel talk at LC'02

Maintaining Beam on the Gold Orbit

- This is necessary to keep spot size small.
  - Geometric aberrations
  - Dispersive growth
  - Wake field tails
- Can use localized fast trajectory feedbacks
  - Time scale of seconds
- Must have global trajectory control with a time scale of minutes
- Must be automatic.
- Must be reliable, robust, ignoring faulty BPMs.

Emittance growth vs. time

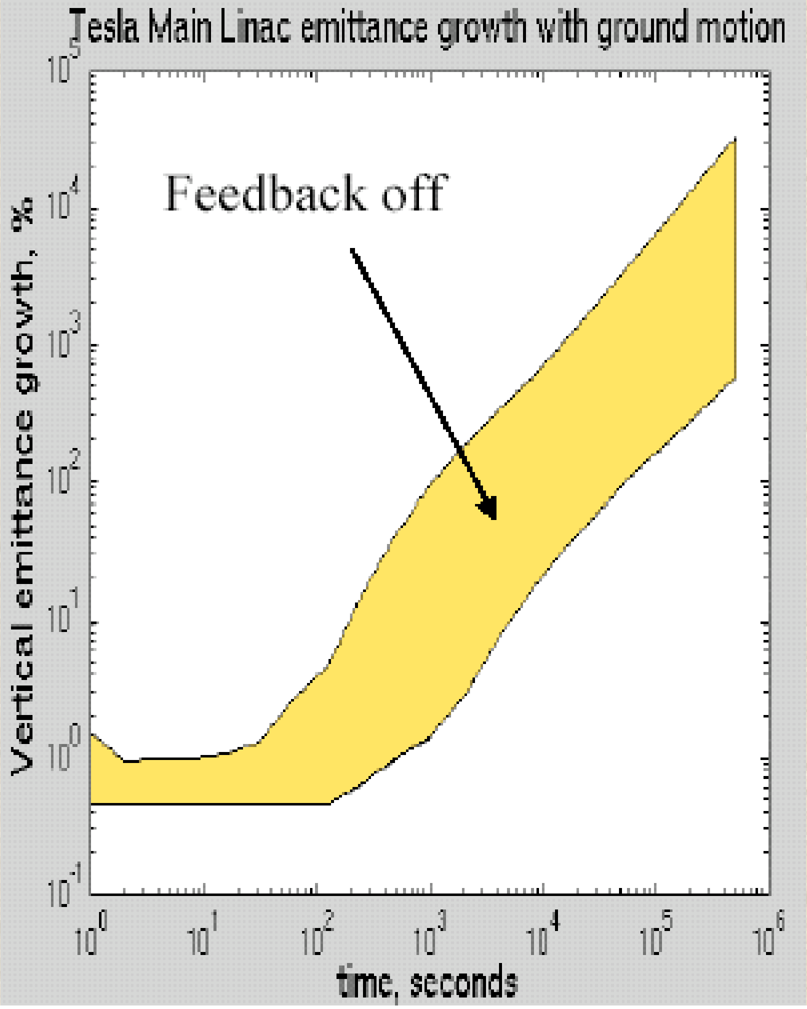
NLC medium ground motion


NLC Main Linac emittance growth, 250GeV

Feedback off

Feedback off

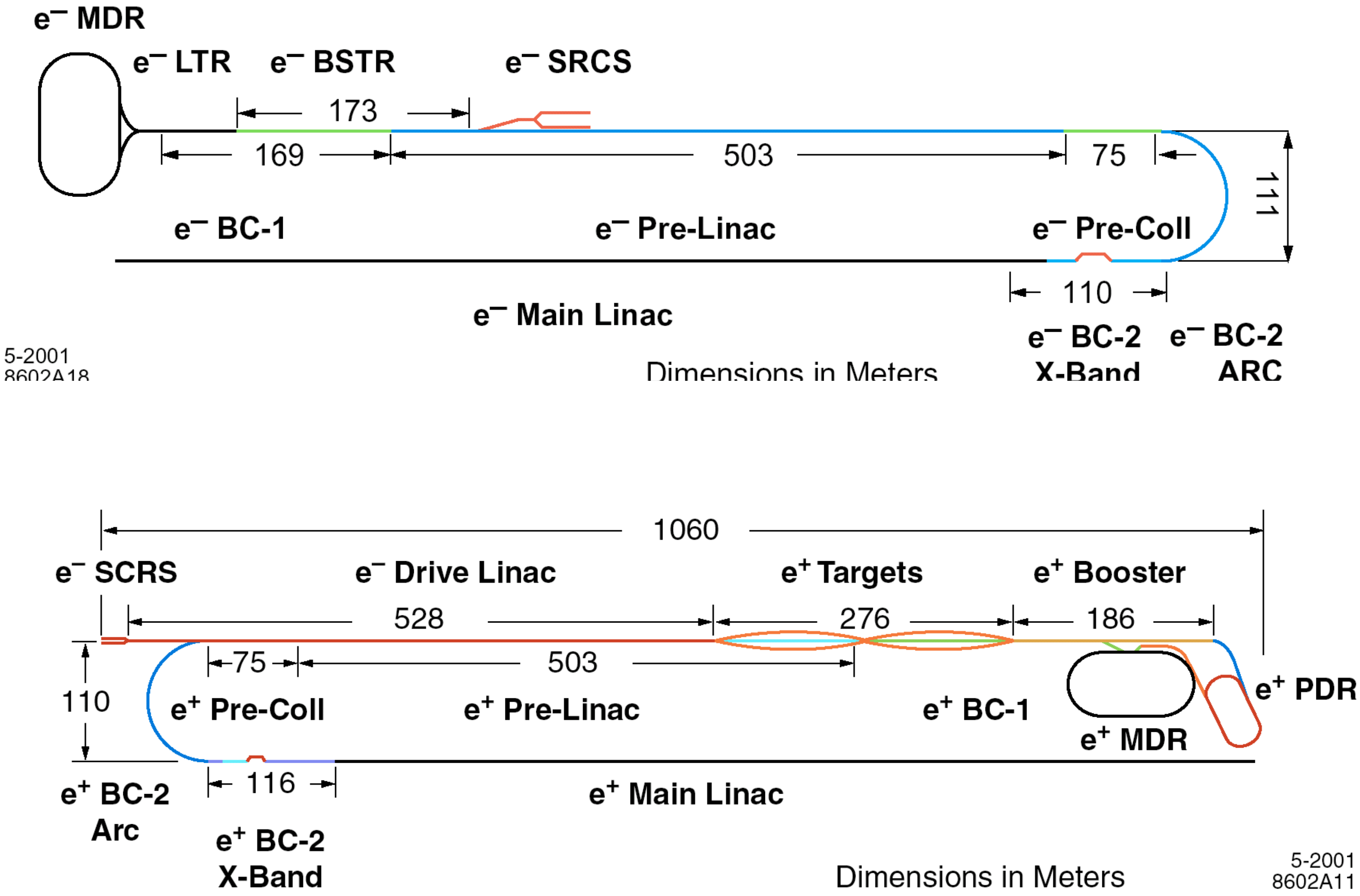
TESLA large ground motion


Tesla Main Linac emittance growth with ground motion

Feedback off

Potential R&D

- Pre-linac collimation systems-these systems are included in all designs but the details have not yet been worked out.
- Such systems will be very important in limiting the beam tails coming from the DR’s.
- They will have to be designed in close coupling with the BDS collimation systems.



NLC injector layouts, showing precollimation sections