ILC Instrumentation and Control
2nd International Accelerator School on Linear Colliders

ETTORE MAJORANA FOUNDATION AND
CENTRE FOR SCIENTIFIC CULTURE

*TO PAY A PERMANENT TRIBUTE TO GALILEO GALILEI, FOUNDER OF MODERN SCIENCE
AND TO ENRICO FERMI, "THE ITALIAN NAVIGATOR", FATHER OF THE WEAK FORCES*

How does one monitor beams with micron precision?

→ position and profile monitors.

Novel instrumentation: laser wires, etc.

Marc Ross, FNAL

Instrumentation

1. Beam position
   - ILC divides in 2 parts:
     - → low emittance (DR, Linac, Beam Delivery)
     - → injector (e+/ e-)
   - ILC will have 2000 cavity BPM’s and 4000 button / stripline BPM’s
   - Cavity BPM’s for low emittance
   - Accelerator Higher Order Modes (HOM) BPM’s

- Beam profile
  2. Transverse
     - emittance
  3. Longitudinal
     - Energy spread and bunch length and correlations (banana)

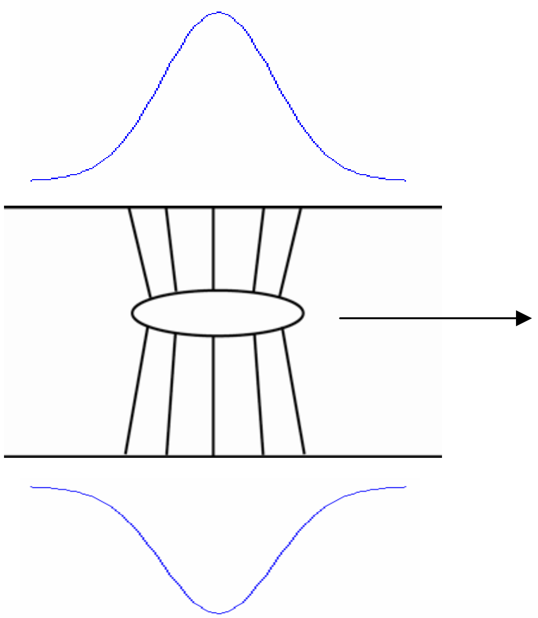
Specifying Position Monitor Performance

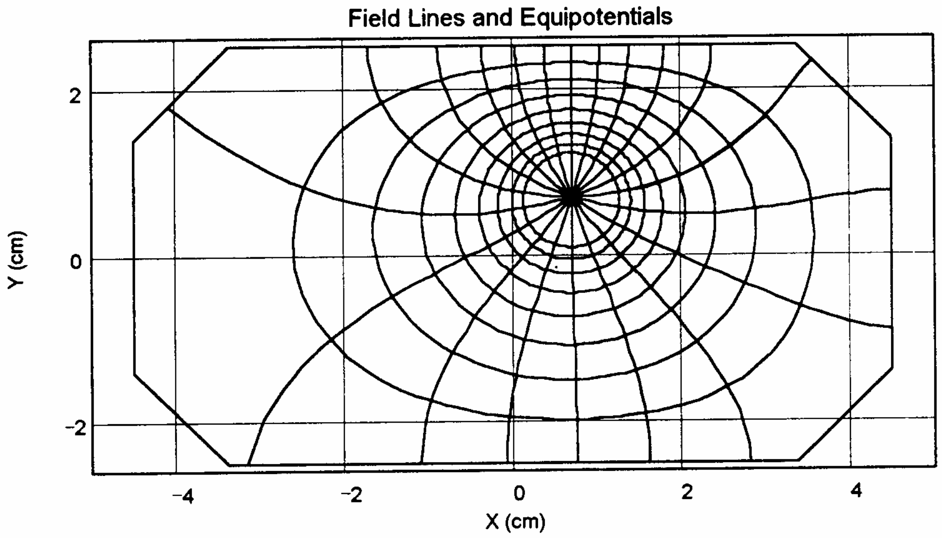
- Critical performance characteristics:
  - Dynamic range (position, intensity)
  - Resolution (smallest detectable difference)
  - Accuracy (linkage to external reference) → offsets and gain
  - Stability (timescales)
- Example specifications (SLAC FEL-LCLS undulator):
  - Intensity dynamic range for specs listed below (0.2 to 1 e10)
  - Offset / stability < 1μm over ± 1 mm (1 hour); < 3 μm (24 hours)
  - Resolution < 1 μm
  - ‘Operational’ intensity dynamic range: > 14 dB; > ± 1mm

Specifying Position Monitor Performance (2)

- LC bunch ‘formats’ range from 300 MHz (DR) to 3 MHz (linac) to 5 Hz (train to train / pulse to pulse single bunch)
  - 10^8 variation in data ‘rate’
- will operate with a variable number of bunches
- measurements require
  - *precision* (averaging) and/or
  - *accuracy* (calibration and references) and/or
  - *high bandwidth* (instability searches – bunch to bunch or turn-by-turn) …
  - these requirements span a large range
- Beam tuning instrument v/v diagnostic

Field generated by bunched particles in a metal pipe





In order to allow passage of the particles, the pipe must be evacuated.

The best evacuated pipes are made of clean metal.

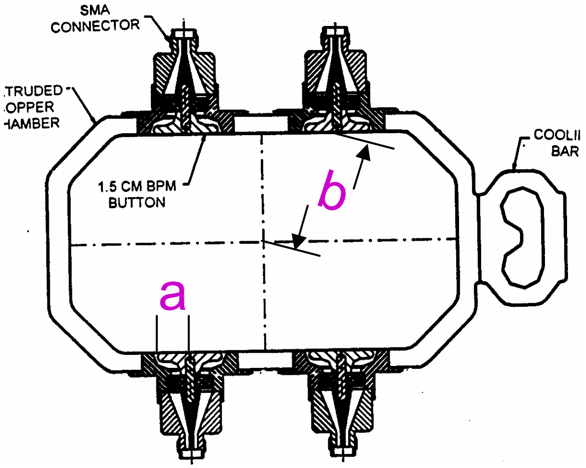
All fields are shielded in a perfect conductor.

Usually we can find out about the beam by sampling those fields.

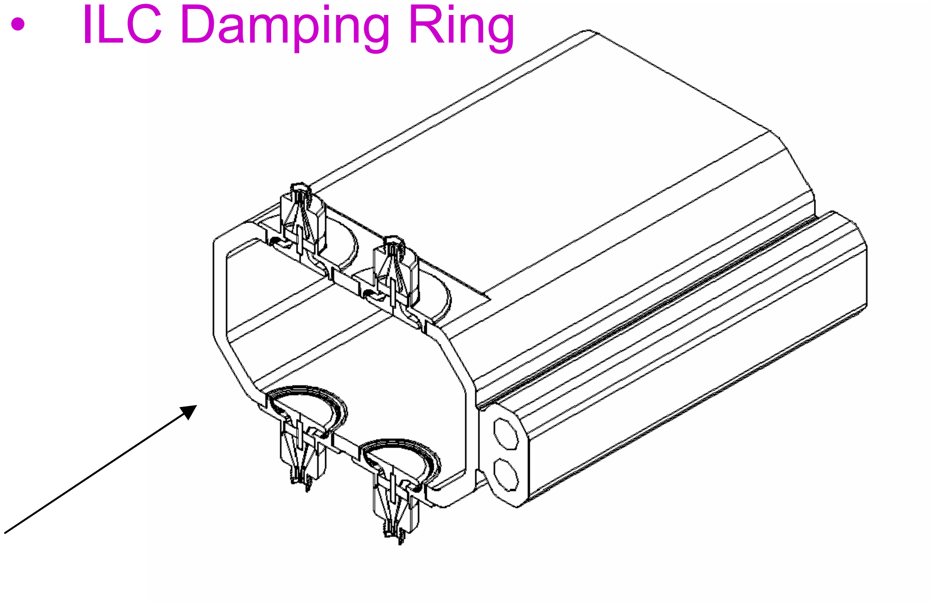
1. Intensity
2. Position ← *Difference between 2 large signals*
3. Size ?

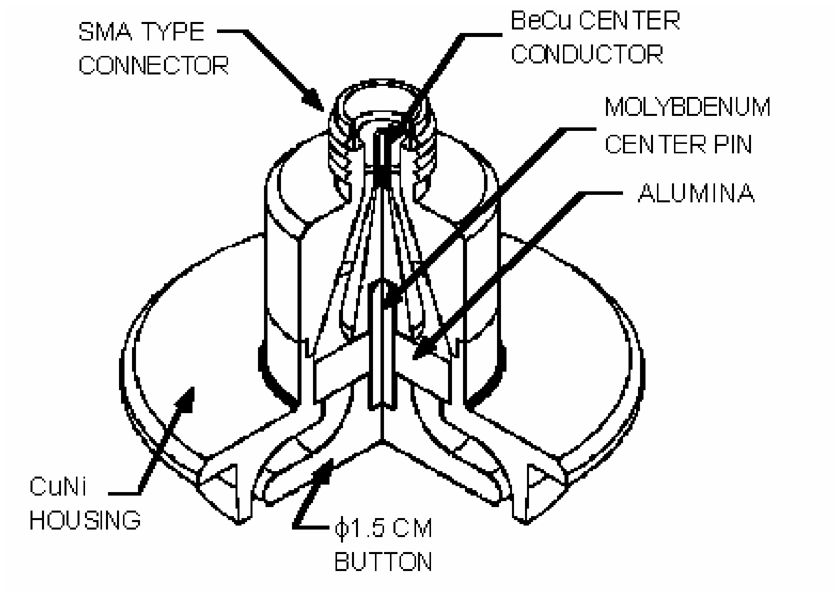
Example BPM system:
PEP II Button Electrodes

- Neatly flared coaxial connection through to the inside wall of the tube
- Recently fell out due heating from *I_rms*
- Fits very smoothly into the wall
  - BPM's are an important component in impedance budget
- ILC Damping Ring



button radius = a
duct radius = b





Position is derived from the difference between 2 large signals

- Centered beam – difference is zero
- Scale: radius (b) ÷ 2

Reference 1

$$x = \frac{b}{2}\frac{V_L - V_R}{V_L + V_R}$$

for small displacements

$$\sigma_x = \frac{b}{2}\frac{\sqrt{2}\sigma_v}{2V} = \frac{b}{2\sqrt{2}}\frac{1}{\sqrt{SNR}}$$

estimator of resolution → offset stability is more important

$$SNR = \frac{P_s}{P_n}$$

Signal to Noise is a power ratio

- We can choose between several extremely different signal processing schemes: take two examples…

Signal basics – start in the ring:

- there is a circulating beam; lowest component *ω_0* is the rotation angular frequency
- electrical power will emerge from the vacuum chamber connector; we can use it in a very simple, slow averaging manner to find position
- Use a frequency domain picture: *ω* is the independent variable

Geometry:

Reference 1

$$Q(\omega) = \frac{Electrode\_area}{Chamber\_radius}\rho(\omega)$$

$\rho(\omega)$ linear beam charge density $\rho_0(\omega)e^{i\omega t}$

$Q(\omega)$ image charge

$$\frac{d\rho}{dt} = \frac{i\omega}{c} I(\omega)$$

ω /c is the ‘distance scale associated with *ω*

Signal basics: from inside the pipe to the cable…

$$I_{img} = \frac{\pi a^2}{2\pi b}\frac{i\omega}{c} I(\omega)$$

right hand term is geometric: dimensions A/A

$$V = IZ$$

Ohms law for accelerator specialists

$$I(t) = I_{avg}\left[1 + 2\sum_m A_m \cos(m\omega_b t)\right]$$

Fourier expansion of ring current; A is nearly 1 up to ~ $m\omega \approx 1/\sigma_z$

$$V_b = \frac{\pi a^2 Z}{bc} 2A_m f_0 I_{avg}$$

for each *m*; a comb spectrum

- At ATF, f_0 is 2.16 MHz and 1/sig_z ~ 35 GHz, so there are many ‘lines’ in the spectrum → coherent motion of the beam causes ‘sidebands’ near each line.

Reference 2

What quality is our signal?

$$SNR = \frac{P_s}{P_n}$$

at ATF, the single bunch power is weak; we must average many turns → 'narrow band' process

$$P_s = \frac{1}{2}\frac{V^2}{Z}$$

$$P_n = k_B TZB$$

Thermal noise → *B* (bandwidth) must be carefully understood (in this case B is low; we are averaging)

- f_0 = 2.16e6
- a=5mm
- b=12mm
- Z=50 ohms
- A=1 → just look at one term

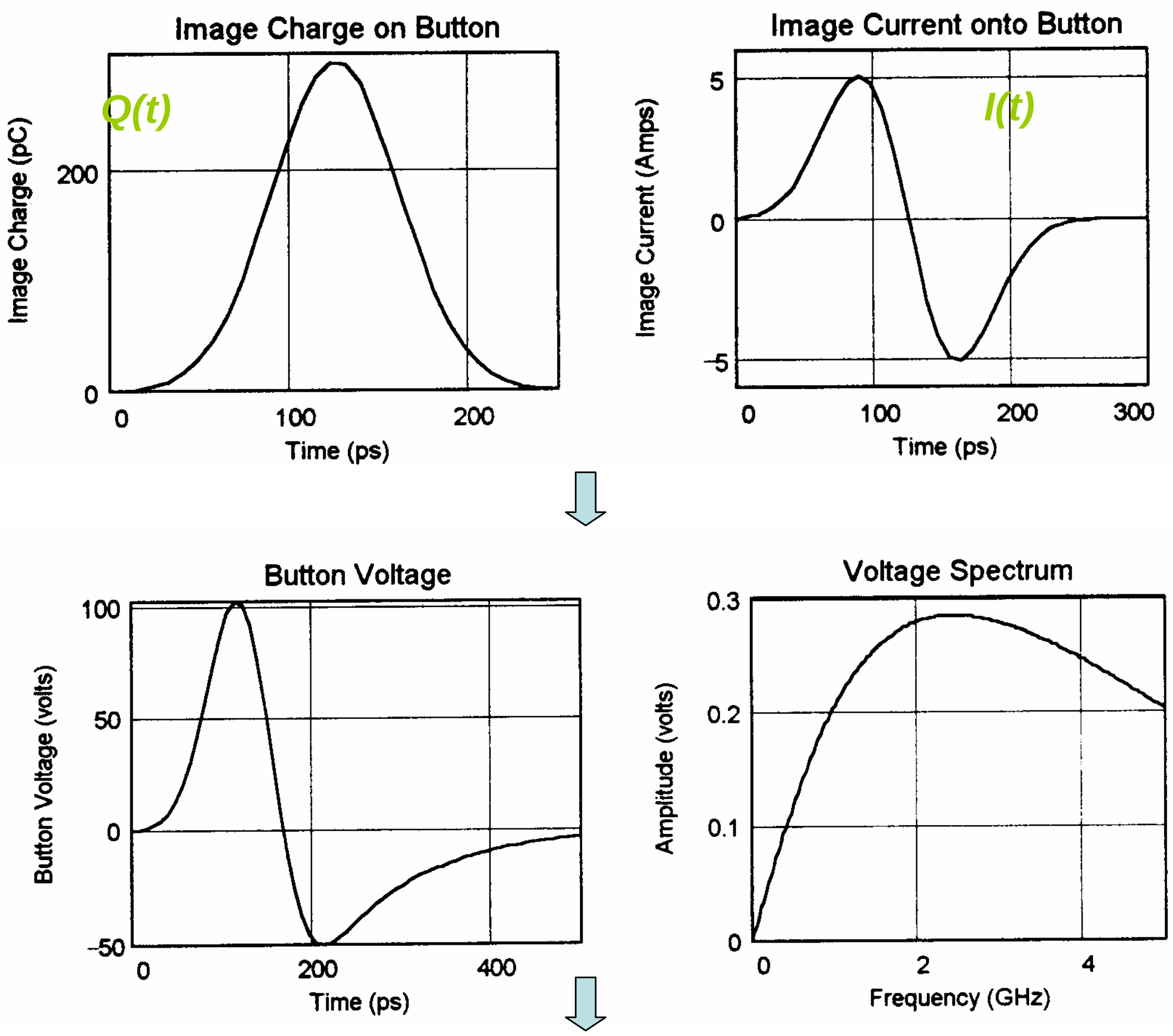
- I = 3 mA
- average 10^4 turns
- SNR ~67 dB (factor of 2000 in voltage)
- 2 μm resolution
- typical synchrotron light machine BPM system

Alternative signal processing – use *peak* rather than average power (broadband)

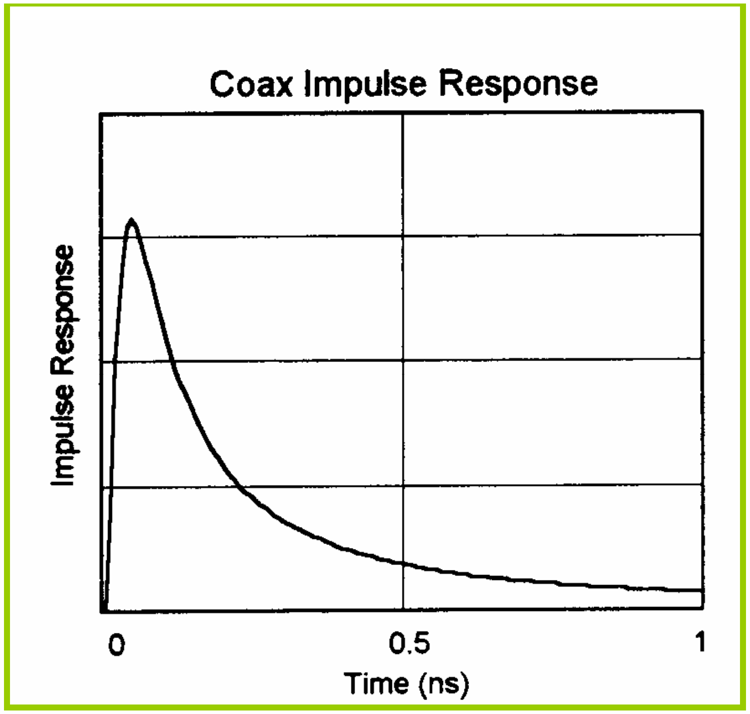
- signal *sampling* and, if needed, digital averaging
- we need single turn information for the ring;
- single bunch, single pass information for the rest of ILC
  - average power is extremely low (f_0^2)

- Often have dual systems (KEK B)
- Graphical, modeled analysis (again taken from PEPII example):

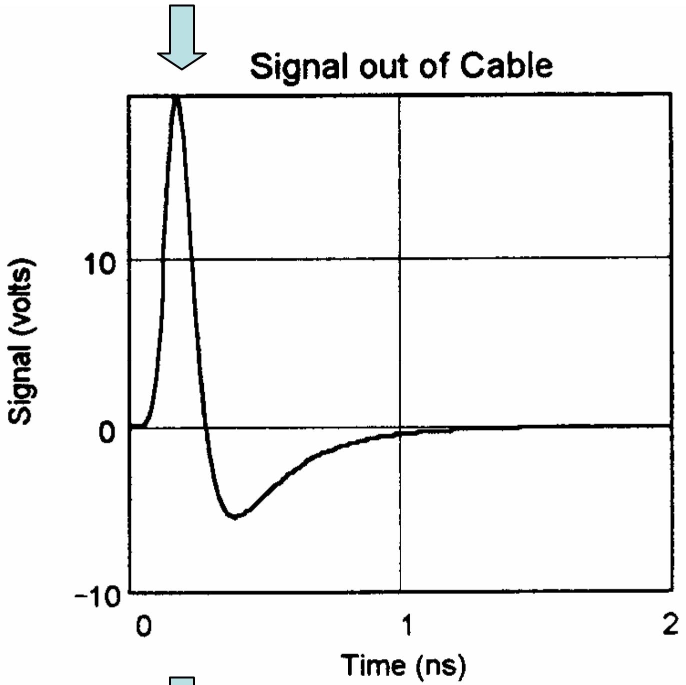
Wide band PEP2 system



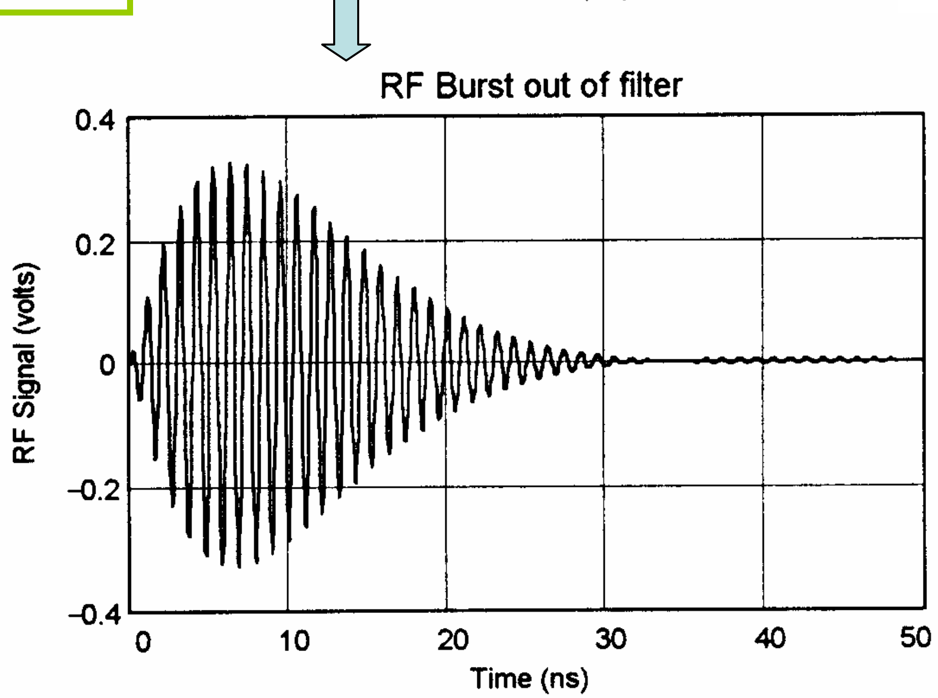
bunch I	8e9 e-
a	5 mm
b	44 mm
sig_z	10 mm



Coax Impulse Response



Signal out of Cable



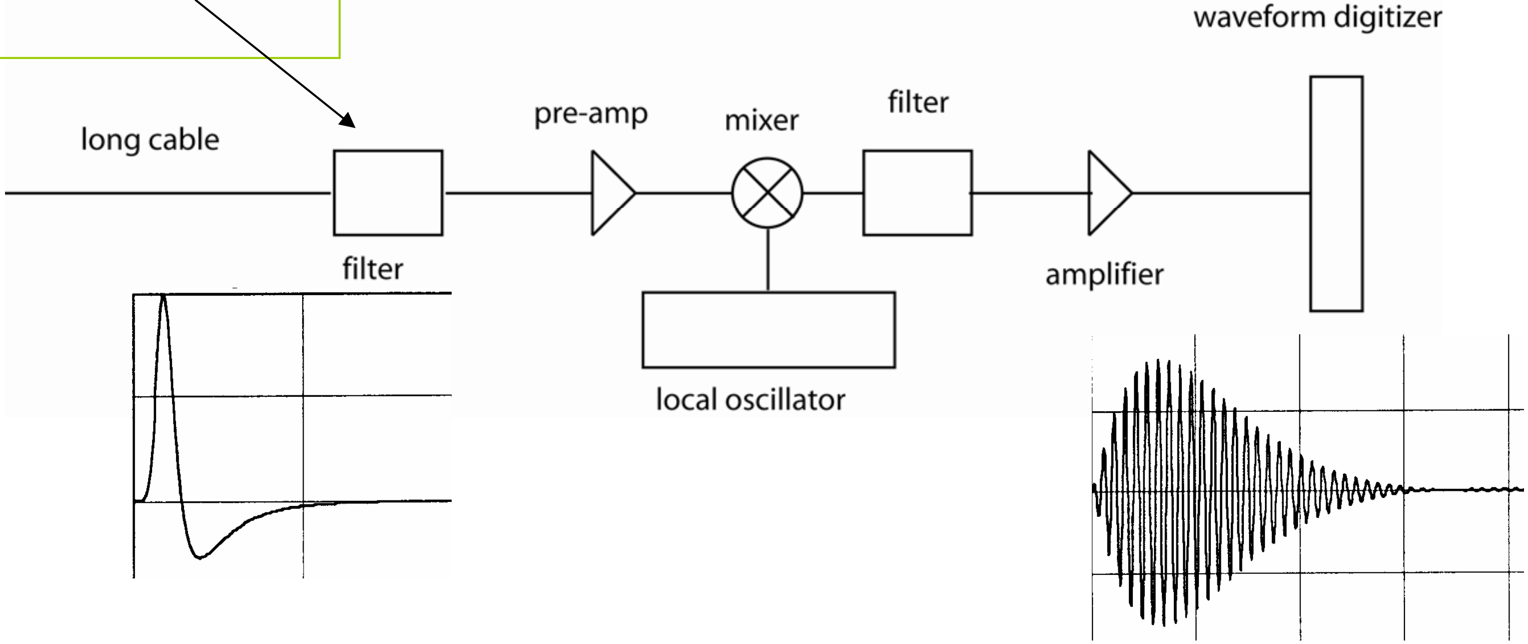
RF Burst out of filter

Goal: measure the peak voltage to characteristic precision → *desired resolution / pipe size*

~ 1e-5

Receiver circuit:

May be a 'narrow band' or 'resonator' filter

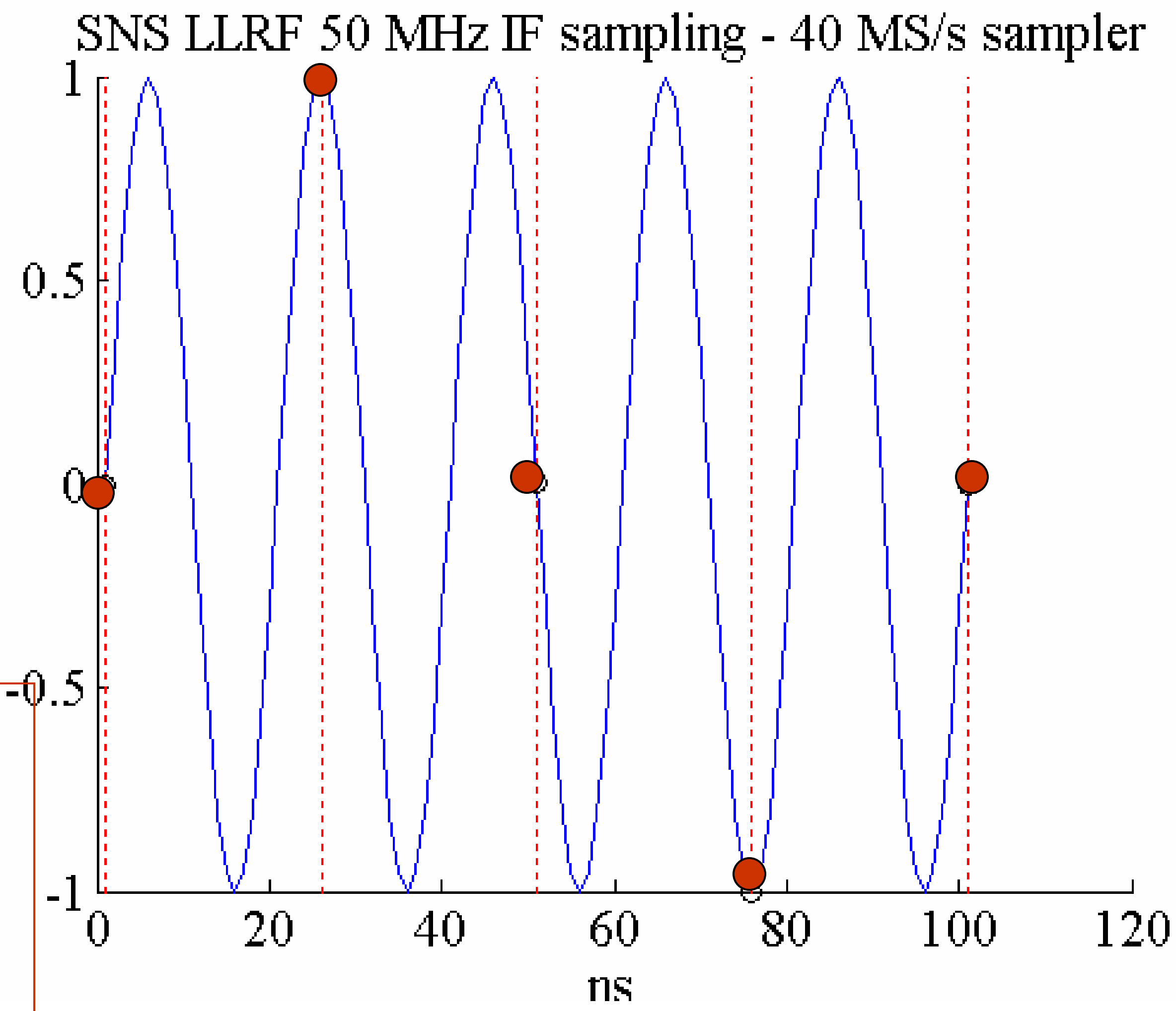


- Receiver adapts the signal for modern digitizer processing
- Nuclear physics 'charge detection' useless for fast, capacitively coupled signal

Direct Digital Downconversion – ‘mixer’

Synchronous
Digital Sampling –

sampling clock
effectively LO
-importance of sampling
clock stability
-(AN-501 Analog
Devices App.Note)
-Clock jitter can generate
spurious signals



Allows *phase* and
amplitude
measurement –

Phase indicates
beam arrival time

Thermal k_b noise is the ideal

- actual performance is usually substantially worse
- ‘Noise Figure’ is the effective degradation with respect to the ideal due to amplifier etc noise.
  - typically 5 to 10 (*power*) in good systems
  - much better in anti-proton stochastic cooling systems

Noise figure – the resolution limit:

$$Noise\_Power = k_B TB$$

$$Noise\_Power = -174 + 10\log(B)$$

$$NF = \frac{(S/N)_I}{(S/N)_O}$$

$$NF = NF_1 + \frac{NF_2 - 1}{G_1} + \frac{NF_3 - 1}{G_1 G_2} + \ldots$$

Noise figure from a sequence of
ganged amplifiers with gain G_i

Wideband system resolution

$$P_n = k_B TZB$$

Use 20 MHz to be consistent with detected signal ↓

$$V_n = \sqrt{2P_n / Z}$$

- V_s ~ 65 mV
- V_n ~ 2 µV

- resolution:

  sig_x ~ 500nm (for PEPII)
  - better for ATF

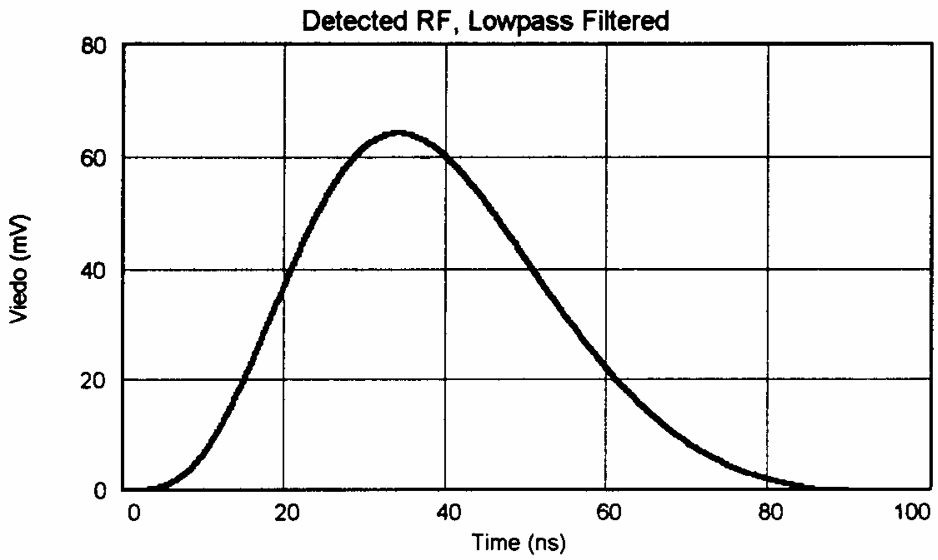
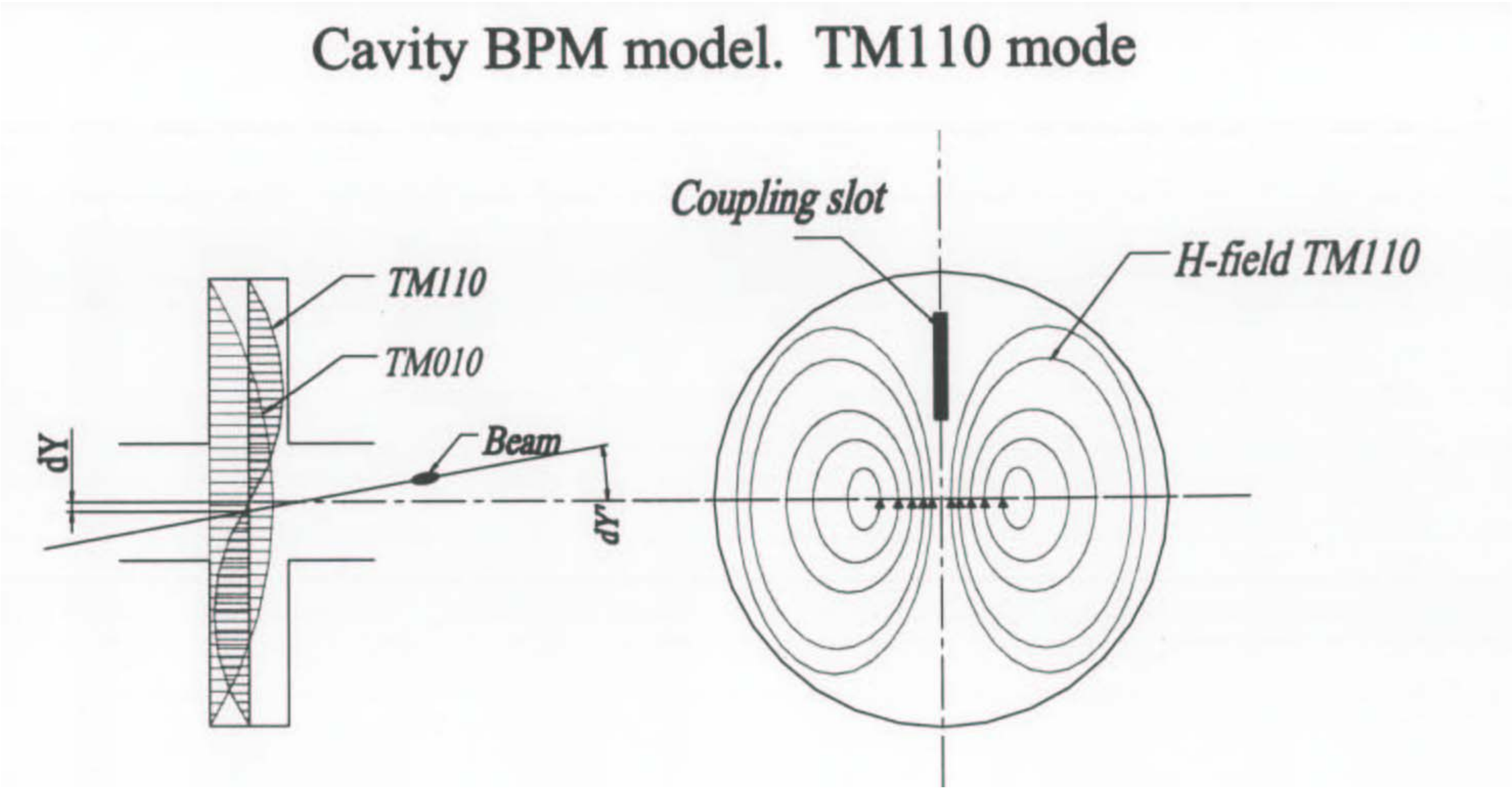


Figure 5. Demodulated RF after 3-pole Bessel lowpass filter

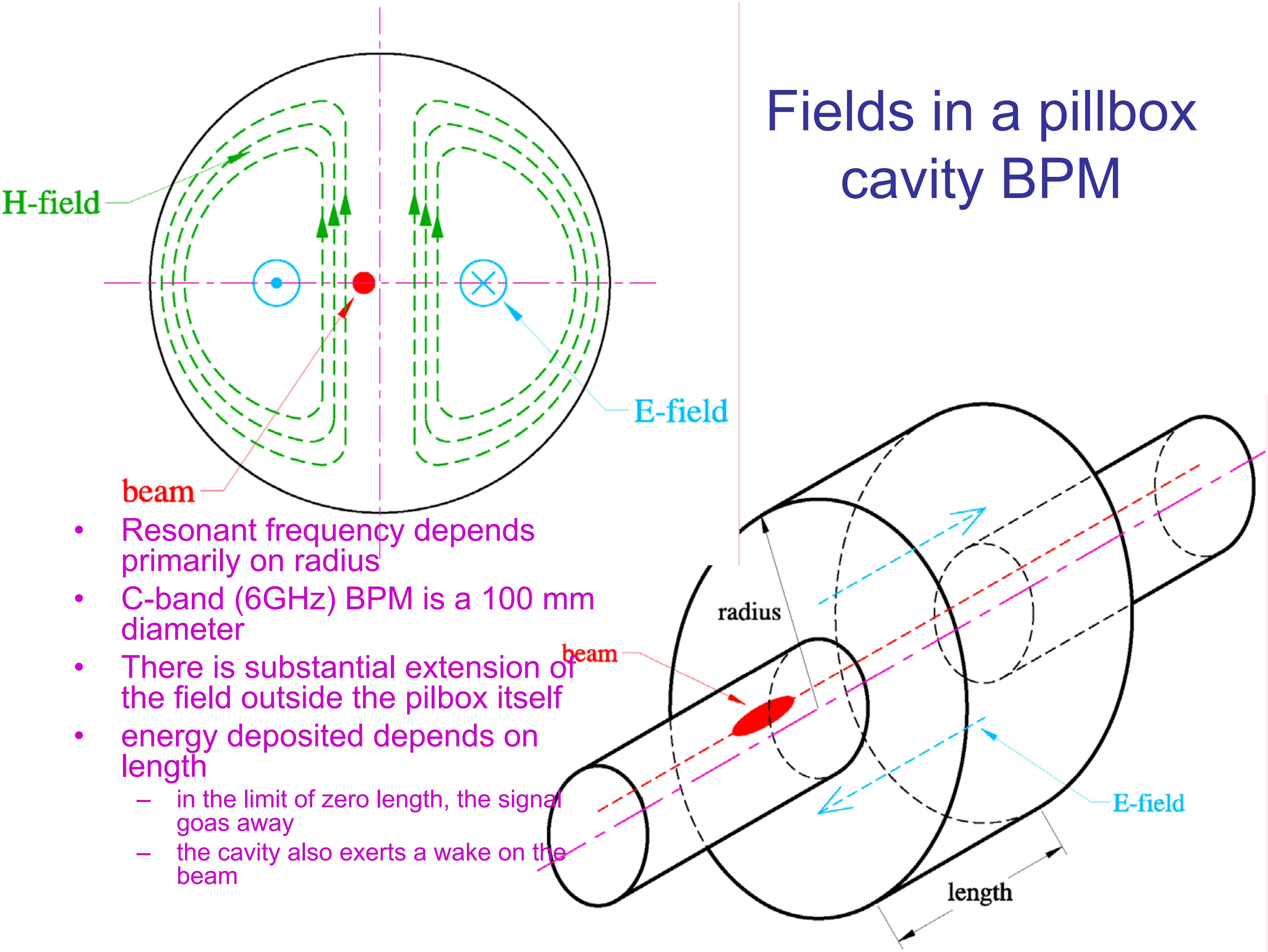
Distort the beam pipe → resonant cavity with output coupler

- Begin the process of adapting the signal for waveform processing → *in the beam pipe*
- This will help remove the *'difference between 2 large signals'* problem
  - all in one design makes detailed diagnostic studies difficult…
  - 'monopole' (TM010) signal can be suppressed through coupler design and frequency filtering
  - Residual is very small
    - Maybe a few microns in present design
    - The equivalent 'monopole' for buttons is r/2 (~cm)

‘Pillbox’ Cavity BPM lowest order modes:

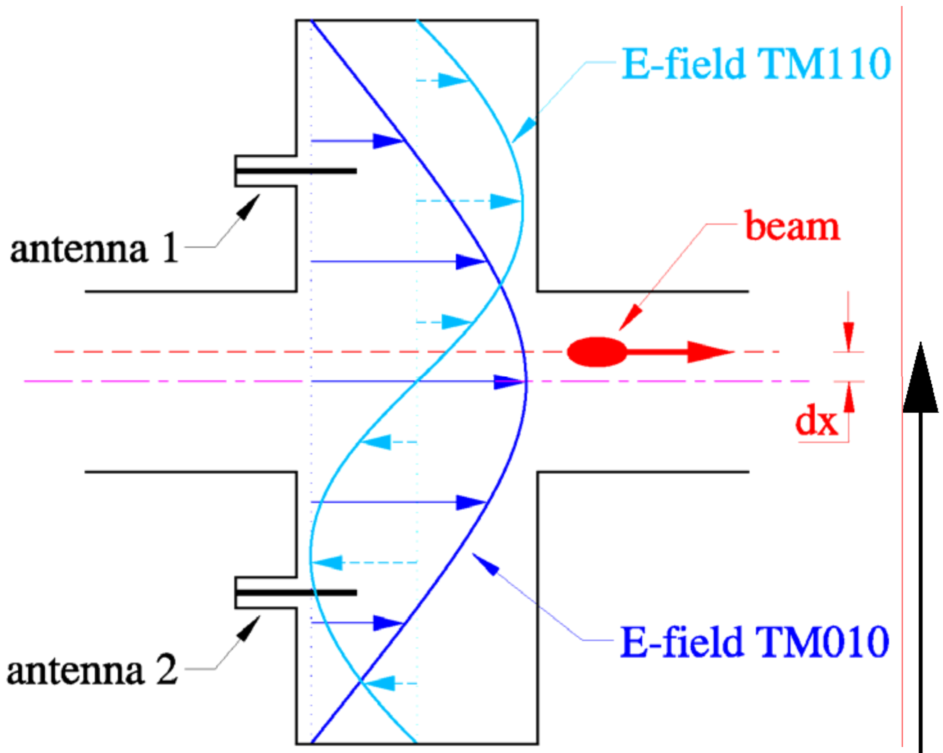


Fields in a pillbox cavity BPM

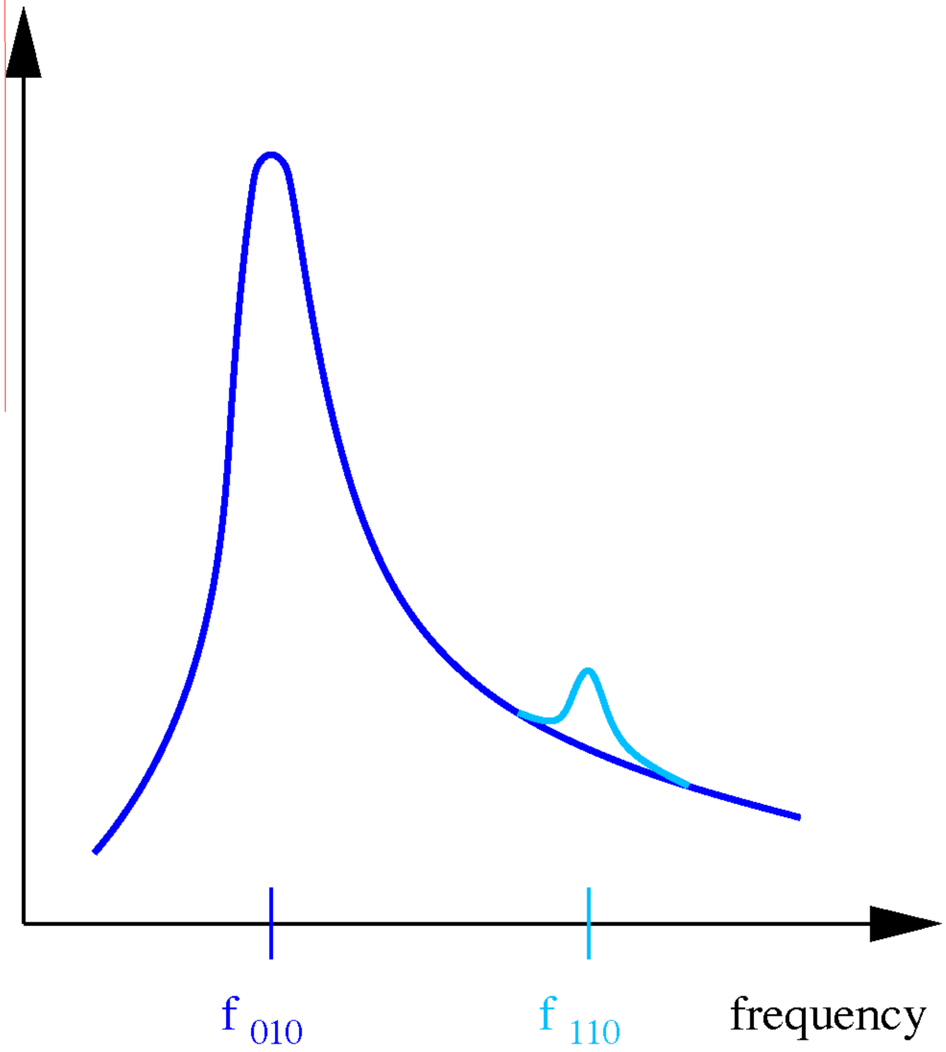


- Resonant frequency depends primarily on radius
- C-band (6GHz) BPM is a 100 mm diameter
- There is substantial extension of the field outside the pilbox itself
- energy deposited depends on length
  - in the limit of zero length, the signal goas away
  - the cavity also exerts a wake on the beam

Modes in the pilbox cavity BPM



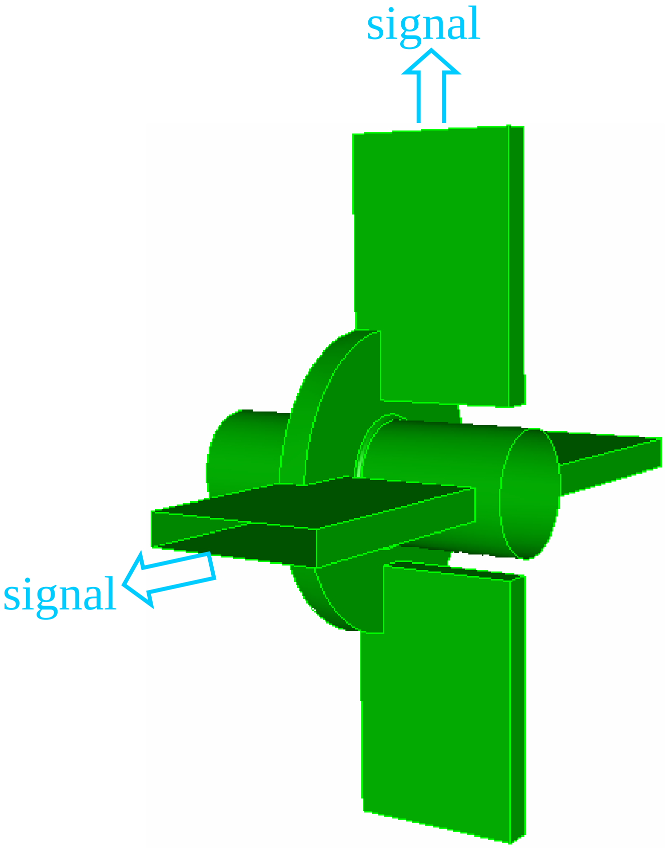
- Cylindrical harmonic expansion
- ‘difference of large’ numbers problem reduced to rejection of the primary fundamental peak
- typical f_{110} / f_{010} ratio 1.4
- only one antenna is needed
- the 110 mode flips phase on either side of the central trajectory



Cavity BPM With TM_{11}-mode Selective Coupler

$$P(q,x) = \frac{V^2}{Z_0} = q^2 \frac{\beta}{1+\beta} \frac{\omega_0 k_{loss} x^2}{Q_L}$$

Charge & position ^2
Power coupled out
Decay time
'loss factor'

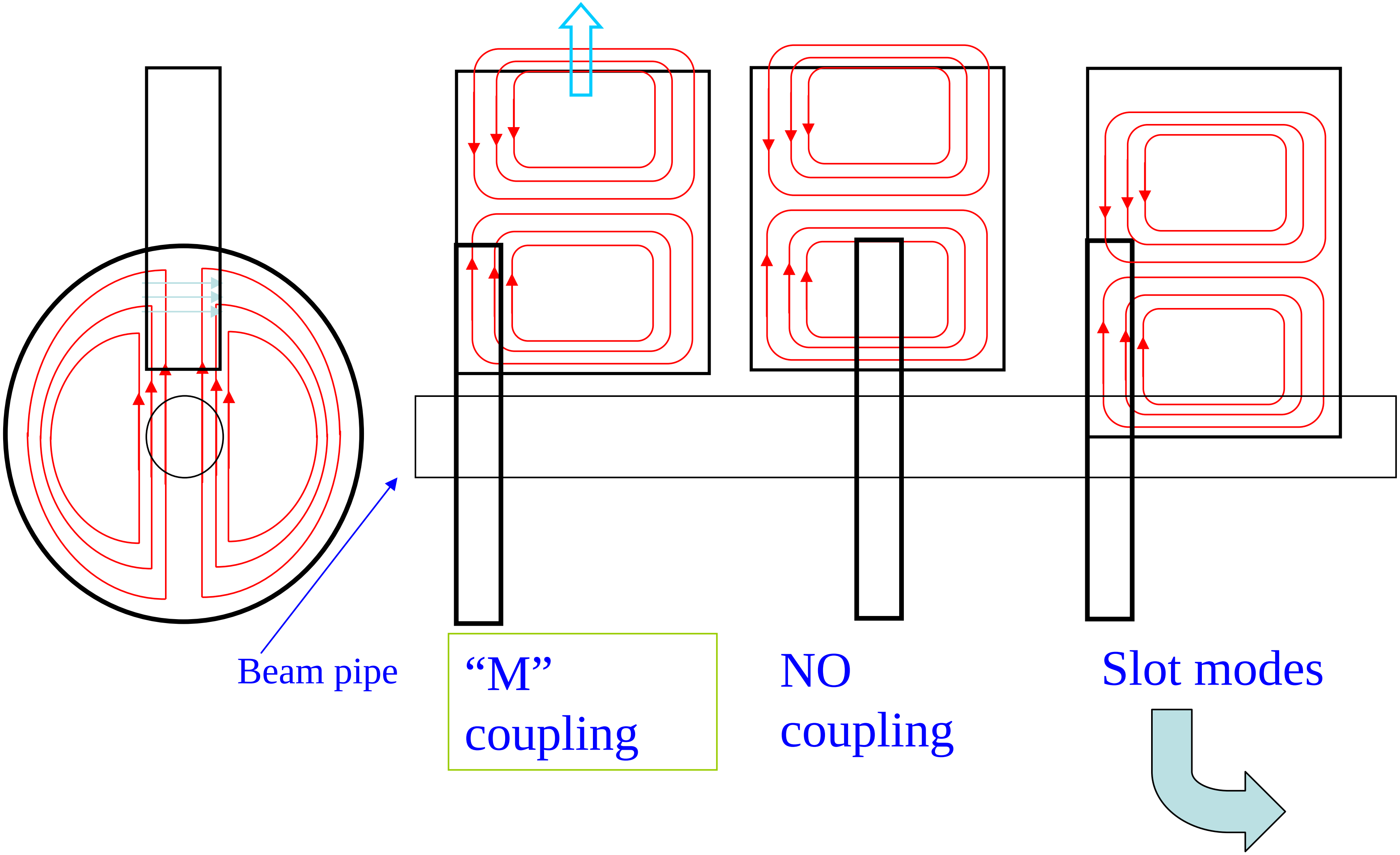


- Dipole mode: TM_{11}
- Coupling to waveguide: magnetic
- Beam *x*-offset couple to *y* port

- Sensitivity: 1.6$mV/nC/\mu m$
  ($1.6\times10^9 V/C/mm$)

- Couple to dipole (TM_{11}) only
- Does not couple to TM_{01}

TM_{11} Selective-coupling Scheme



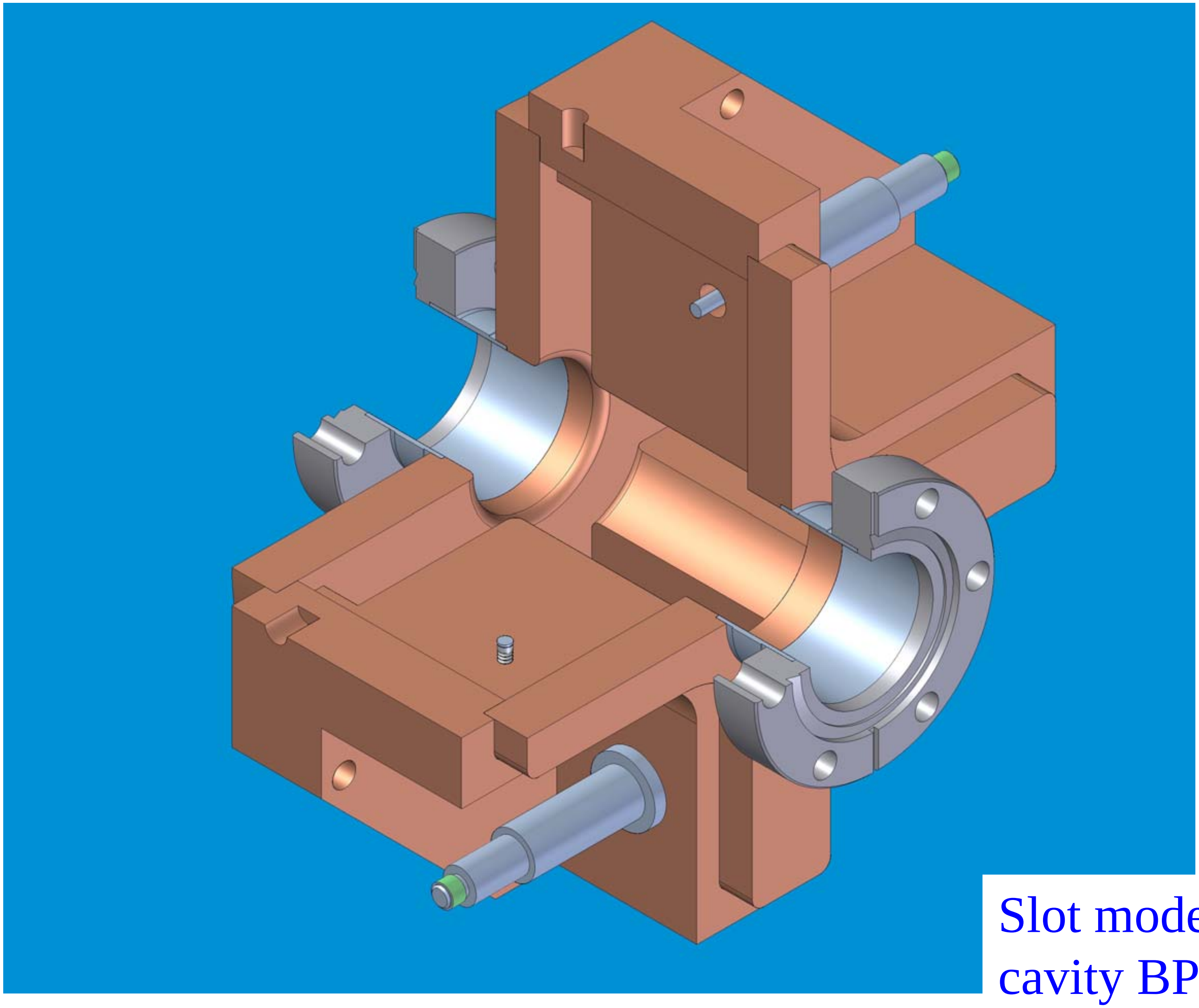
Port to coax

Beam pipe

“M”
coupling

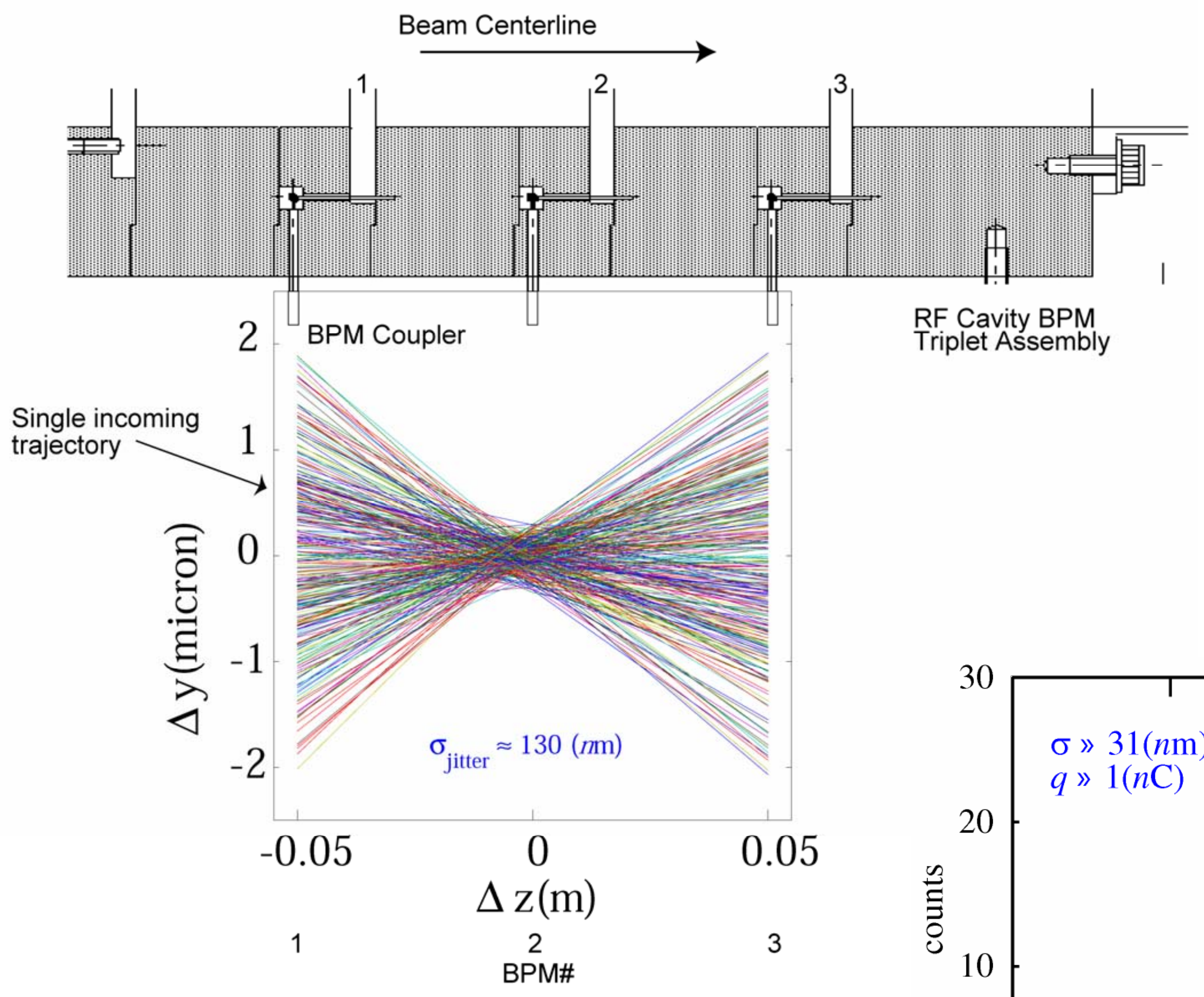
NO
coupling

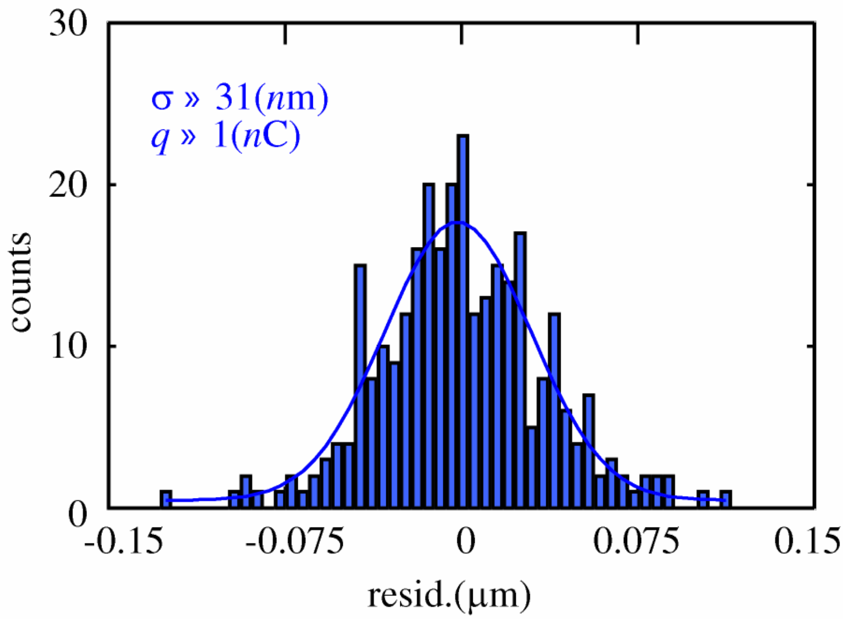
Slot modes



Slot mode
cavity BPM

FFTB IP C-band cavity BPM triplet – this is the way to test BPM performance …

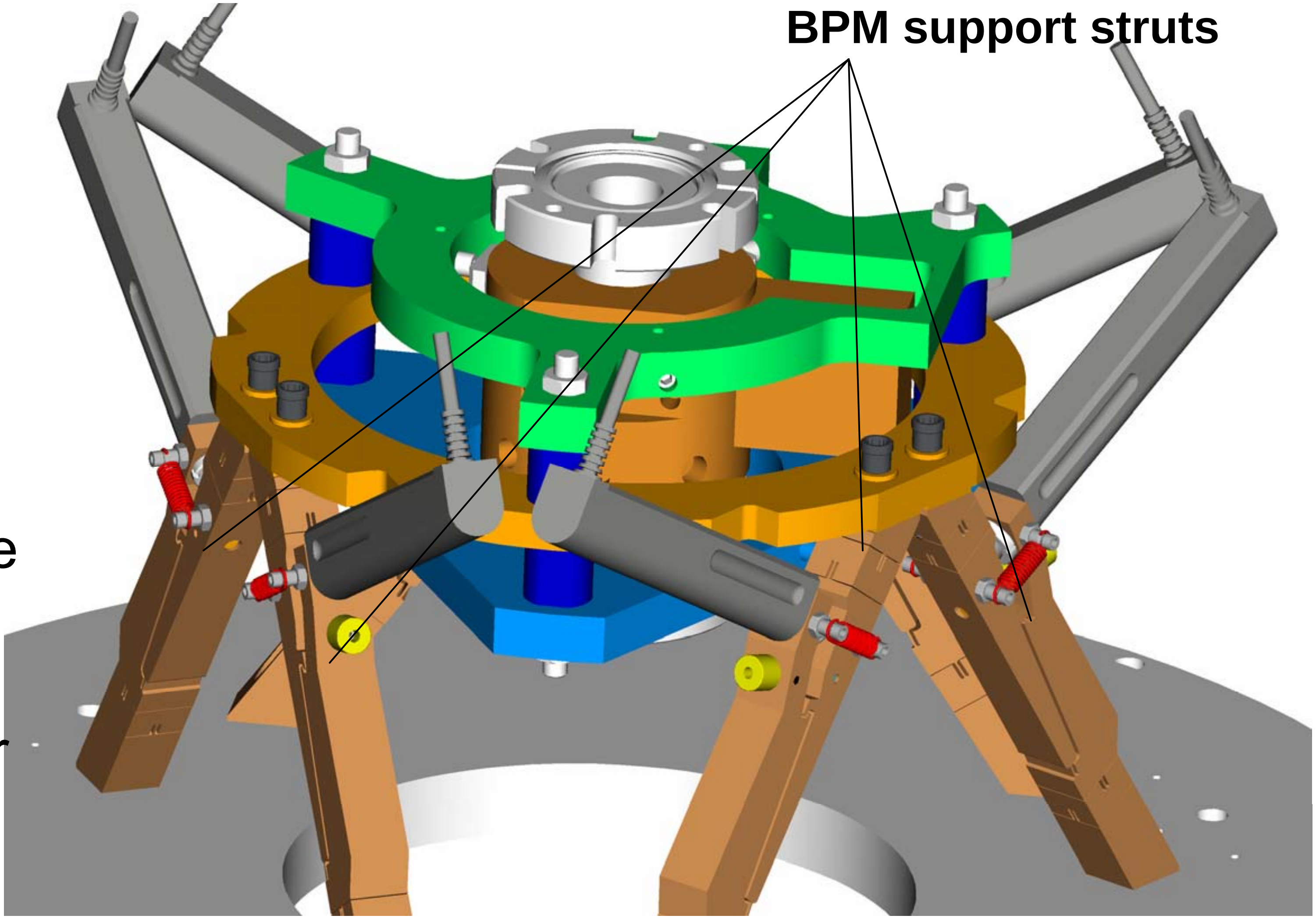




Or …provide independent positioning of each of the 3 BPMs → Ultra-stiff hexapod BPM mover

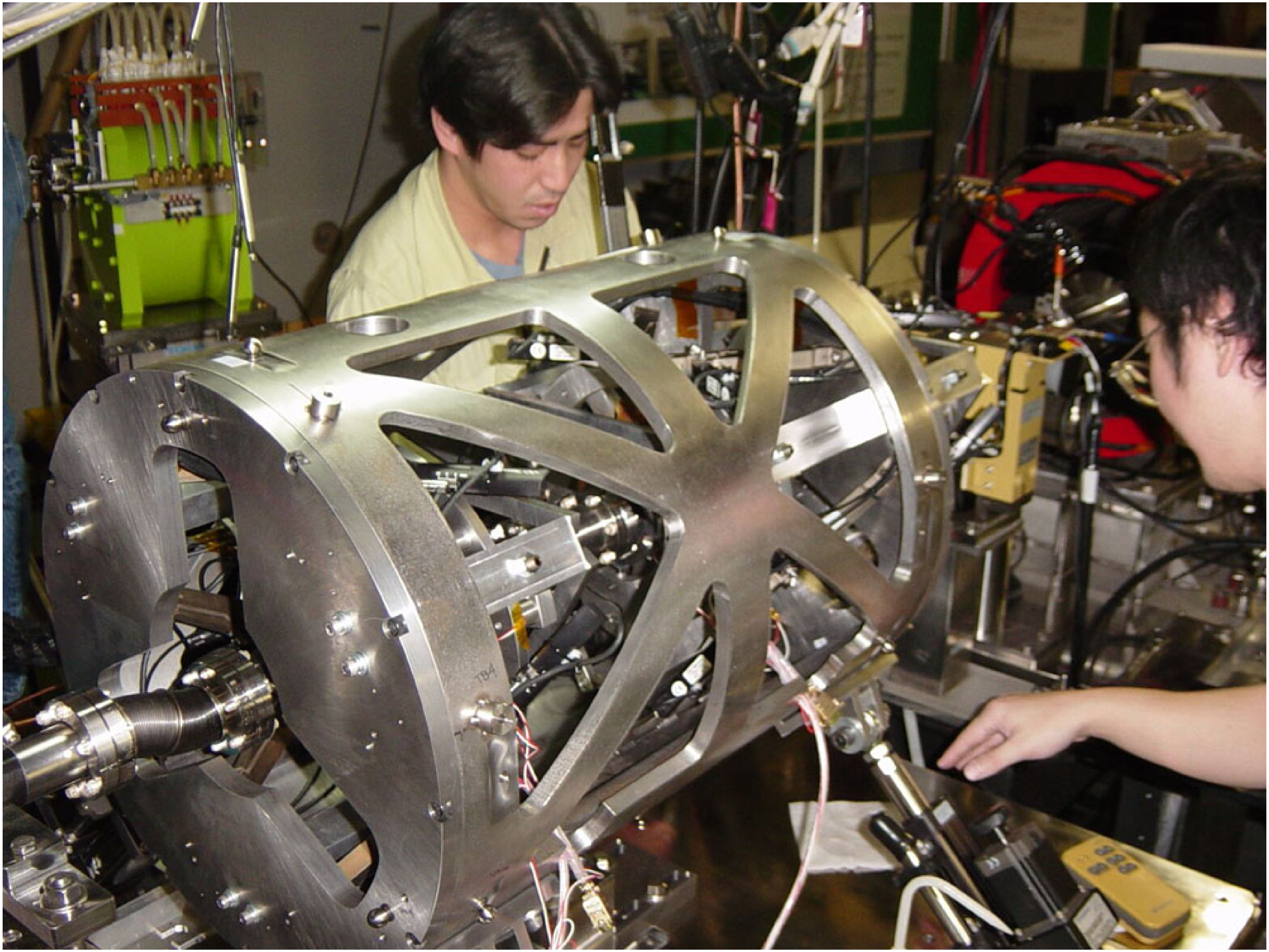
x, x’, y, y’…

with the monopole suppressed → we can begin to see the ‘tilt’ of the trajectory of beam

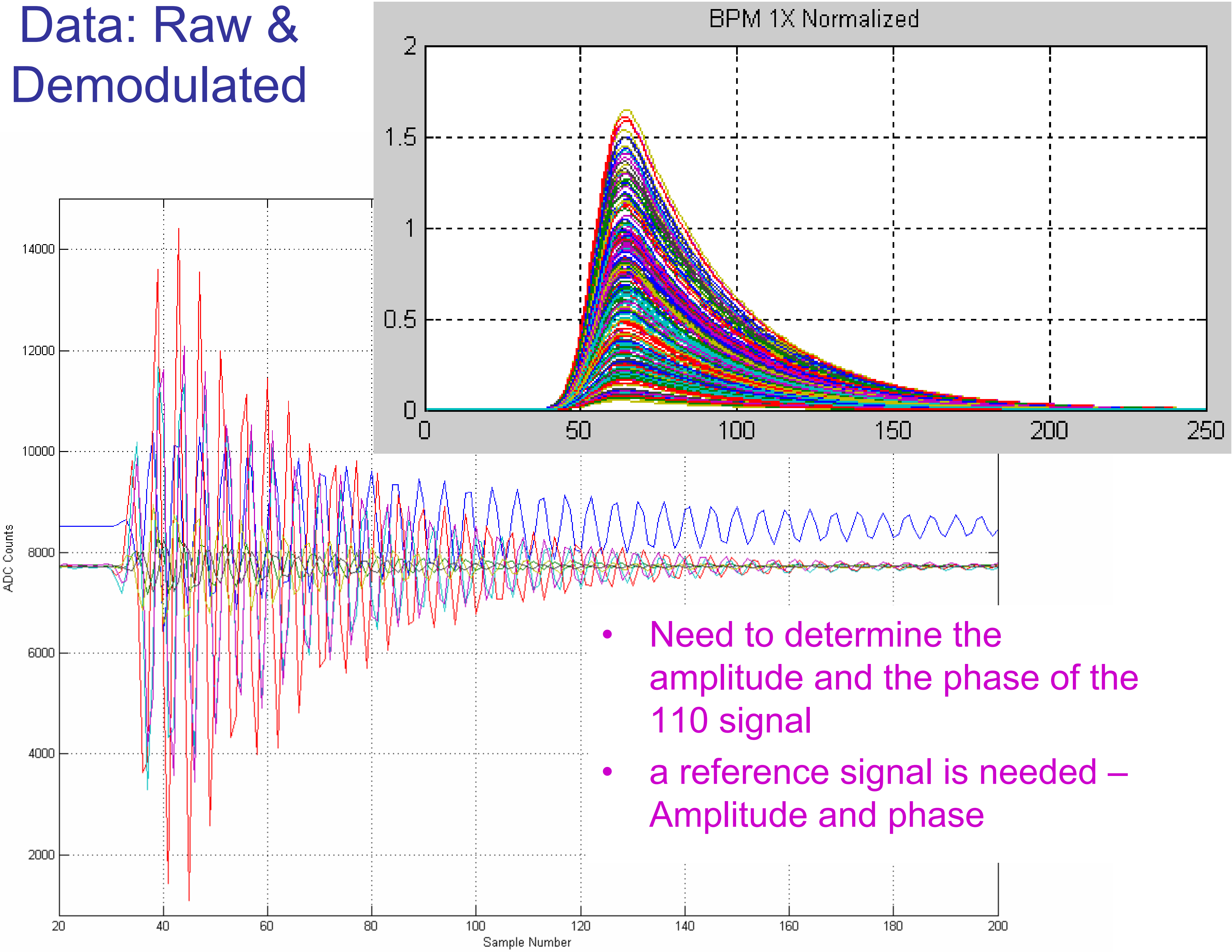


LLNL

Precision flexure struts


TB4

Data: Raw & Demodulated



- Need to determine the amplitude and the phase of the 110 signal
- a reference signal is needed – Amplitude and phase

Estimates: Signal

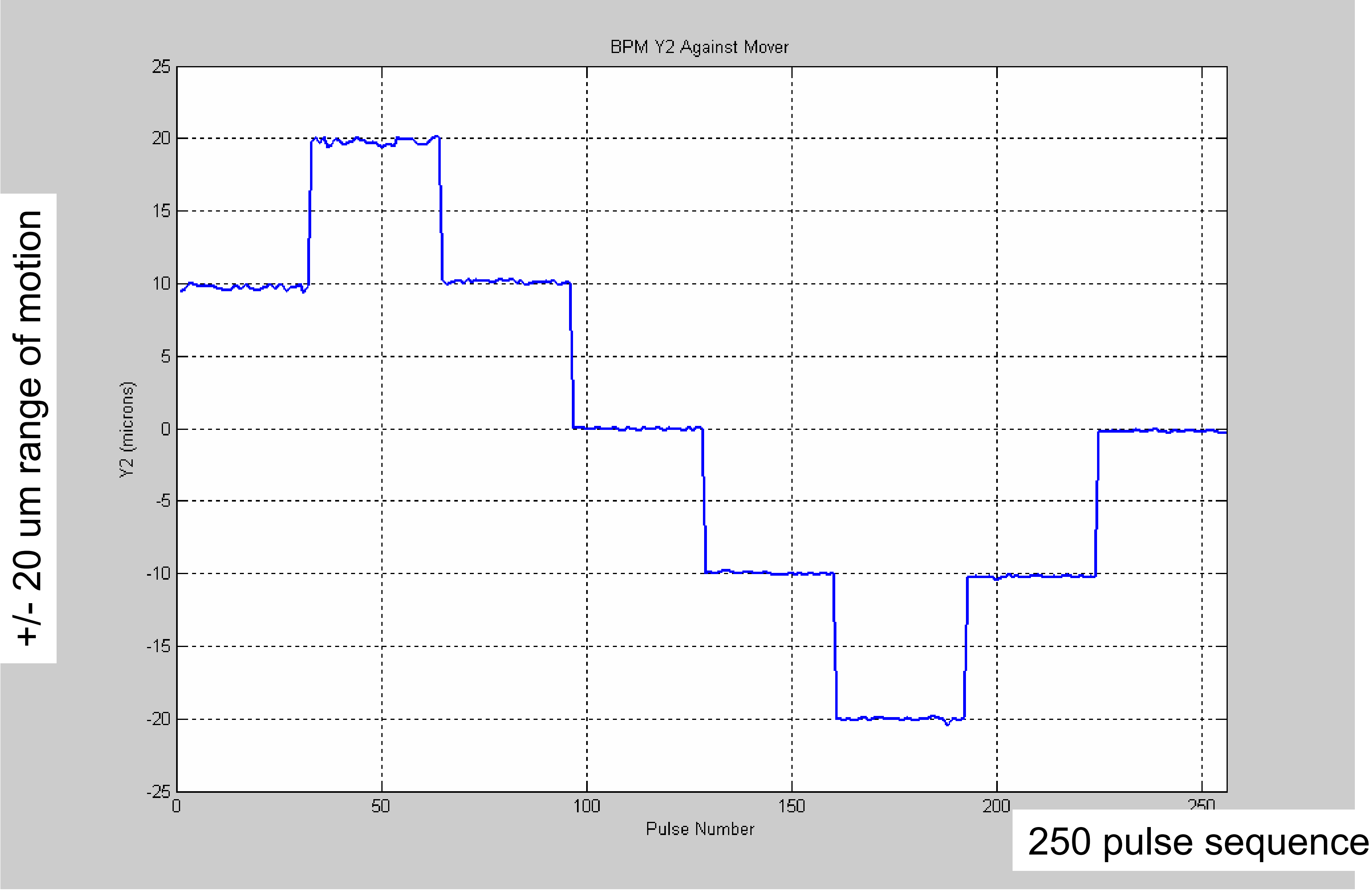
Parameter		Units
Cavity Loss	3.89 x 10^{10}	Joules/Coulomb^2/mm^2
Cavity internalQ	5100	(from V. Vogel)
External Q	3300	
Coupling	.35	β
Energy coupled out	1.37 x 10^{10}	Joules/Coulomb^2/mm^2
Power out at 1 nm displacement over characteristic fall time	1.12 x 10^{-13} (-99.5dBm)	Watts (1 nm, 1 x 10^{10}ppb, 310 ns fall time)
Gain used	2.24 x 10^{5} (53.5 dB)	(June 2003)
Signal strength after amplification	2.52 x 10^{-8} (-46 dBm)	Watts (1 nm, 1 x 10^{10}ppb, measured 310 ns fall time)
Signal strength	1.12	mV (rms – 50 Ohm)
Digitizer counts	9	Counts rms at beginning of decay
Digitizer full scale	913	nm (8192 = 2^{13} full scale)

Estimates: Noise

Parameter			
Thermal noise	-174	dBm/Hz	
IF bandwidth	20	MHz	
Noise in-band	-101	dBm	
System Components	gain (dB)	noise figure (dB)	output noise (V)
Cable	-1.2	1.2	2 x 10 $^{-6}$
Limiter	-0.8	2	2 x 10 $^{-6}$
C-band amplifier	10	7	1 x 10 $^{-5}$
Mixer	-5.5	7.3	6 x 10 $^{-6}$
filter	1	7.4	5.6 x 10 $^{-6}$
IF amplifier and anti- alias filter	48	8.5	.0016
digitizer	0	8.5	.0013 (10 counts)

Calibrate

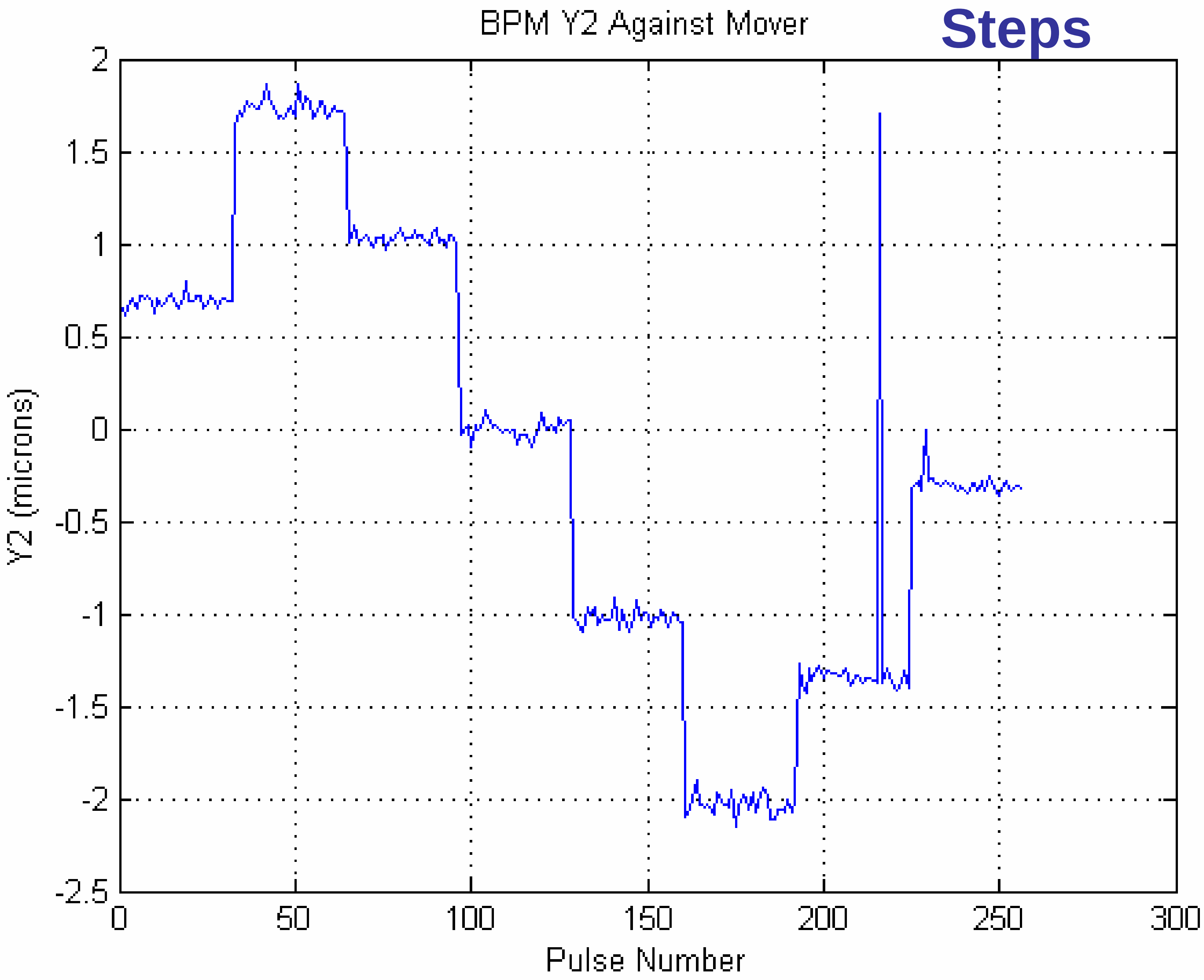
- Move one BPM at a time with movers – plot the residual of the central BPM with respect to the 1st and 3rd
- Extract BPM phase, scale, offset as well as beam motion by linear regression of BPM reading against mover + all other BPM readings.



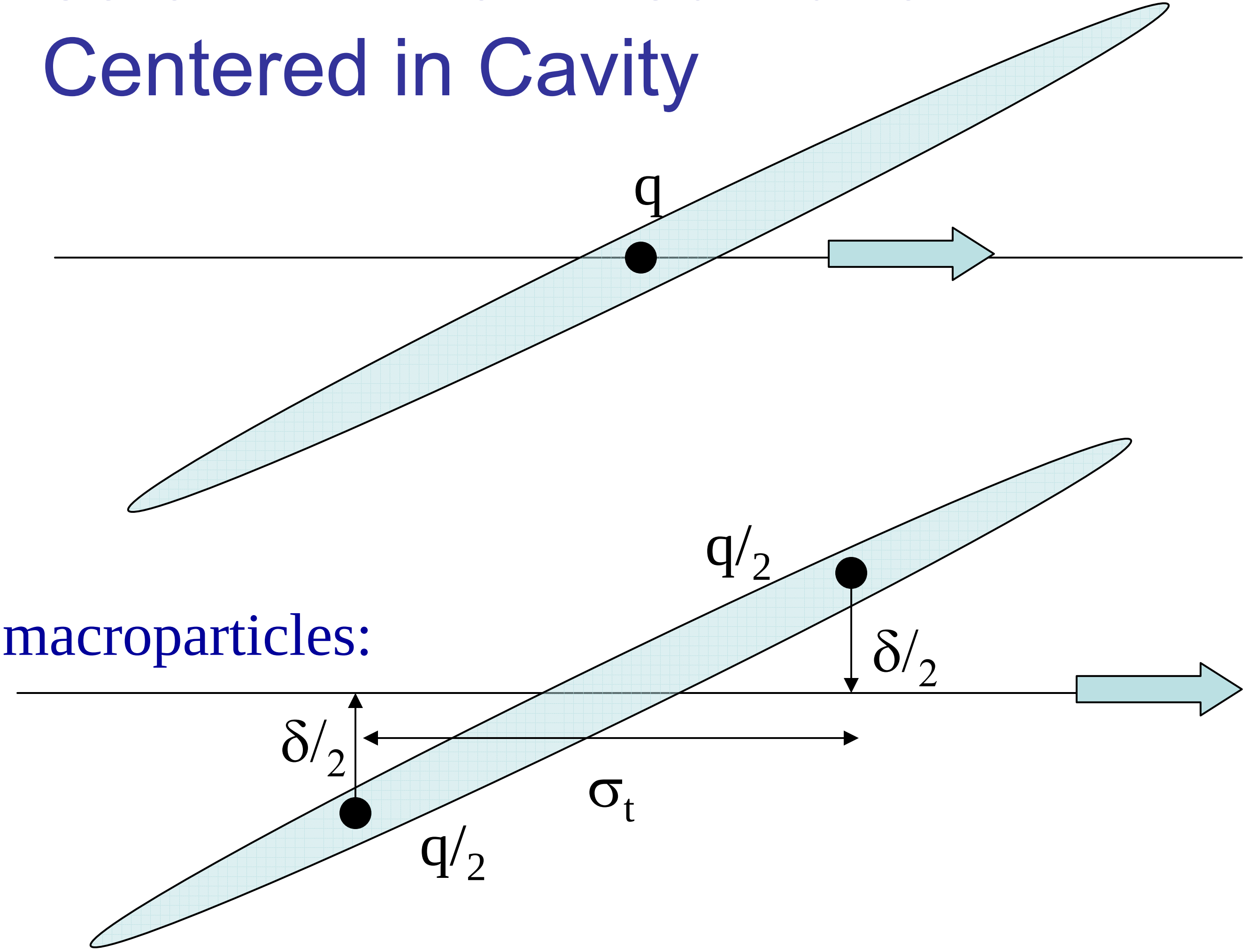
+/- 20 um range of motion

250 pulse sequence

Move BPM in 1 um Steps



Response of BPM to Tilted Bunch Centered in Cavity



Treat as pair of macroparticles:

$$V(t) = a\frac{q}{2}\frac{\delta}{2}\sin\omega(t-\frac{\sigma_t}{2}) - a\frac{q}{2}\frac{\delta}{2}\sin\omega(t+\frac{\sigma_t}{2}) = \frac{a\delta q}{2}\cos\omega t\sin\frac{\omega\sigma_t}{2}$$

Tilted bunch

- Point charge offset by δ

$$V_y(t) = aq\delta\,\underline{\sin(\omega t)}$$

- Centered, extended bunch tilted at slope δ/σ_t

$$V_t(t) = \frac{a\delta q}{2}\,\underline{\cos\omega t}\,\sin\frac{\omega\sigma_t}{2}$$

- <u>Tilt signal is in *quadrature* to displacement</u> ← *'it's phase is orthogonal'*
- The amplitude due to a tilt of δ/σ is down by a factor of:

  with respect to that of a displacement of δ

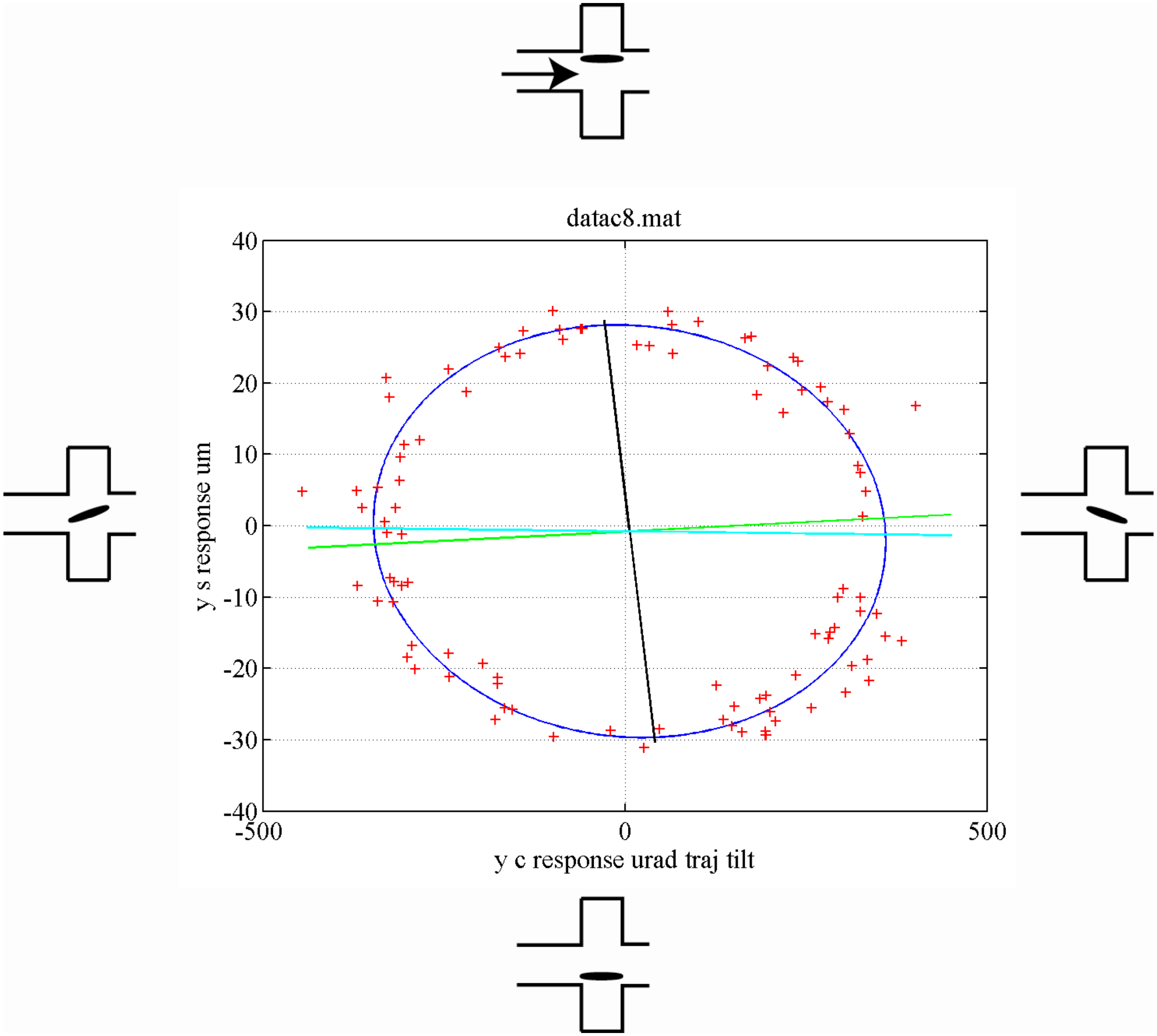
  (~bunch length / Cavity Period)

$$V_t \big/ V_y = \frac{\omega\sigma_t}{4} = \frac{\pi\sigma_t}{2T}$$

2 nanometer resolution with a 200 um beam 1 mrad tilt ('banana') resolution – a potentially powerful tool for linac emittance control

‘Tiltmeter’ test using upstream RF beam-tilter

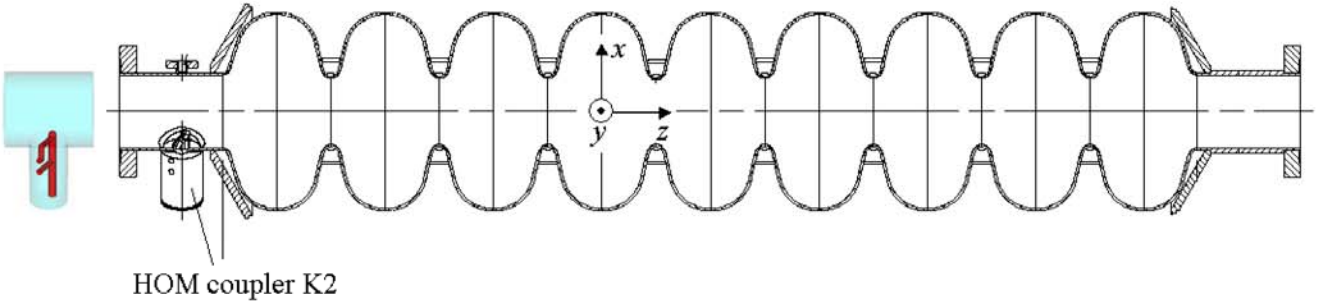
- *Phase and Amplitude* of cavity BPM response with randomly tilted/displaced beam
- Axes show directions of pure displacement (black) and pure angle (bluish) (green is 90 from pure displacement)
  - Tilter motion is not quite orthogonal
- Also works for angled trajectories

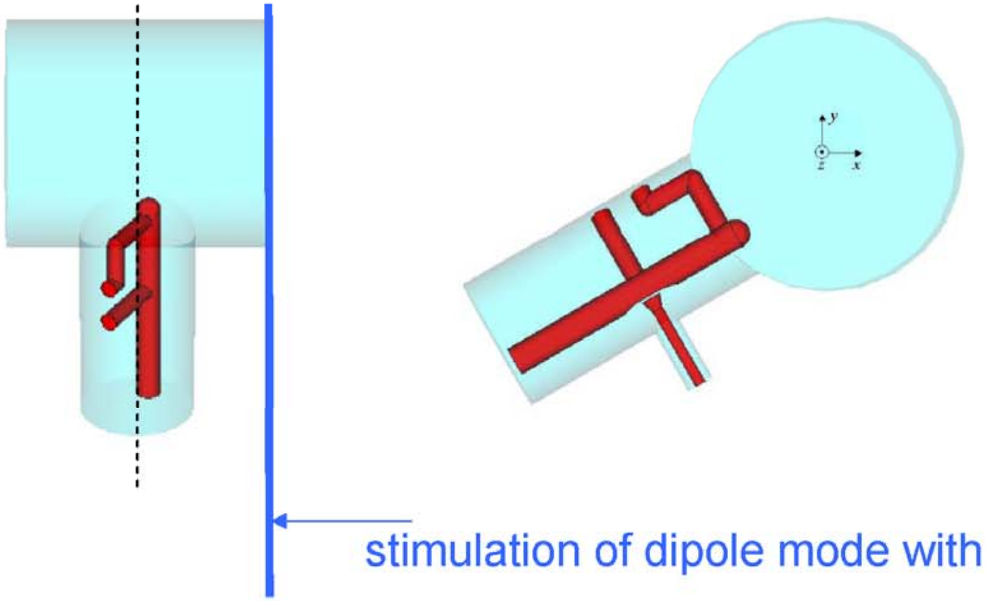


Superconducting RF cavity Higher Order (read dipole) Modes: ‘HOM’s

- A superconducting cavity also provides position signals
- The 9 cell ‘pill-box’ accelerating structure has a ‘cylindrical’ harmonic set of electromagnetic fields
  - a series of 9 eigen-mode bands
  - ‘shock excitation’ by strong ‘delta function’ electron bunch excites them all with varying strength
- Some can be coupled out with field probes
  - Careful not to extract the *extremely strong* accelerating field
- The beam can be used to probe the *assembly* of the cryomodule

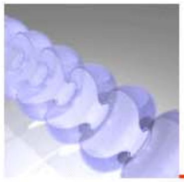
perfect TTF cavity + upstream HOM coupler



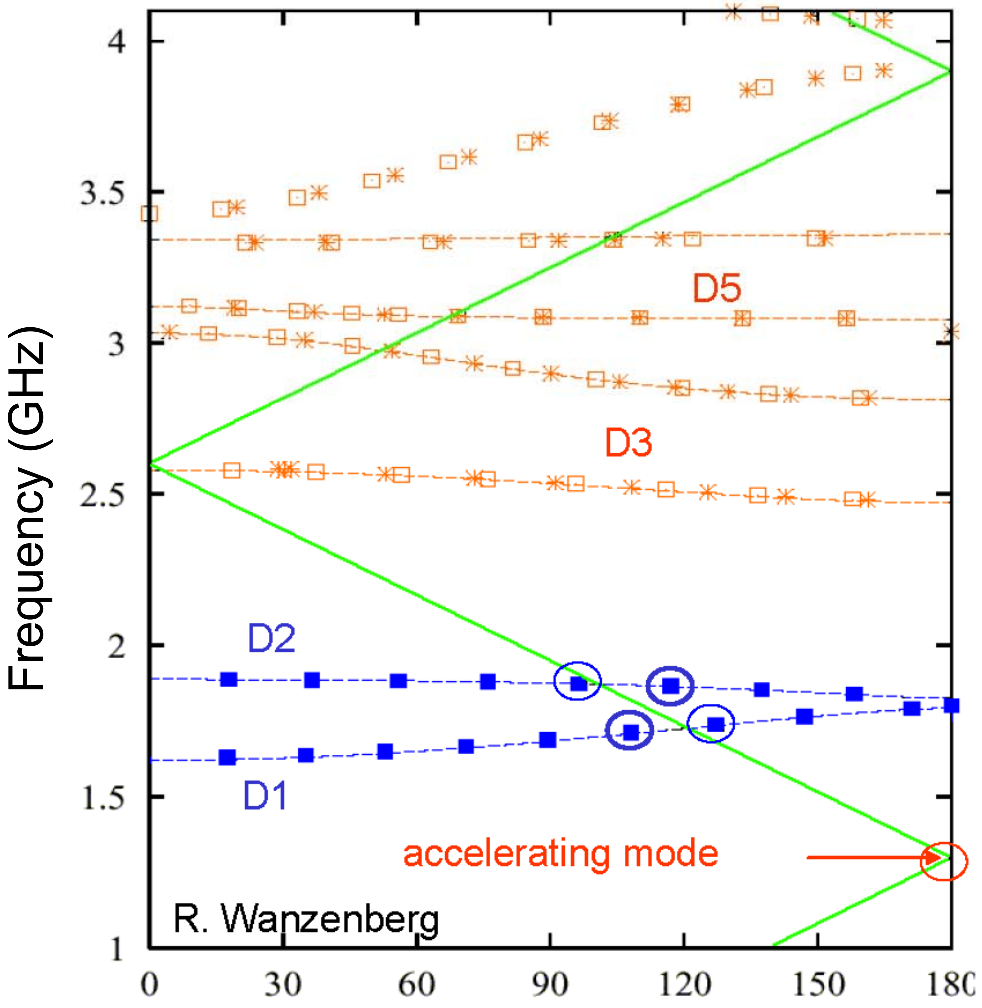


stimulation of dipole mode with horizontal polarization

DESY M. Dohlus Aug 2004



TTF 9-cell cavity HOMs

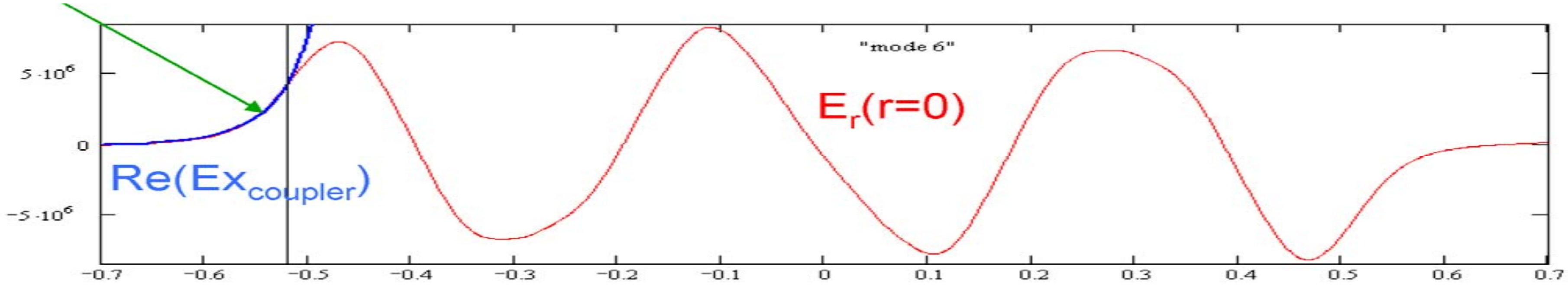


Modes Below cutoff

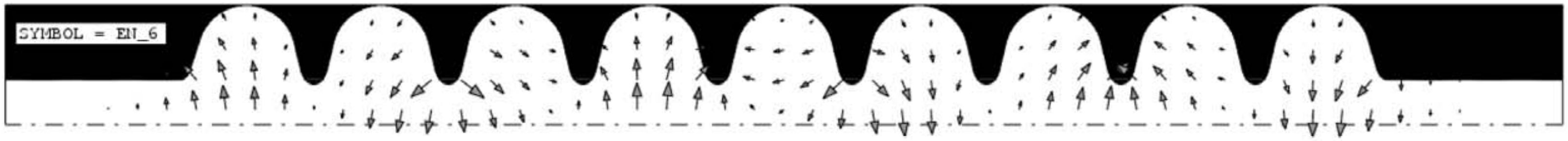
⇒ no propagation

⇒ R/Q easy to compute
in one cavity.

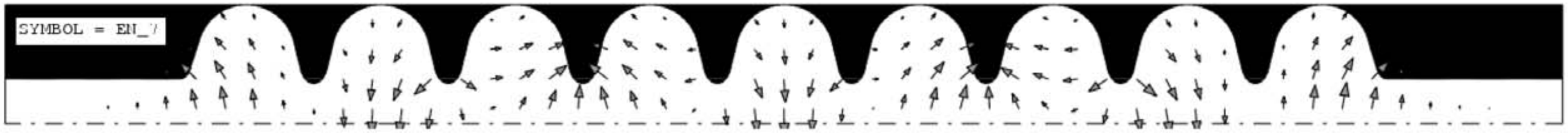
	Frequency [GHz]	R/Q [Ω/cm2]
TE111_6	1.705	11.1
TE111_7	1.730	15.6
TM110_4	1.865	6.4
TM110_5	1.875	9.0



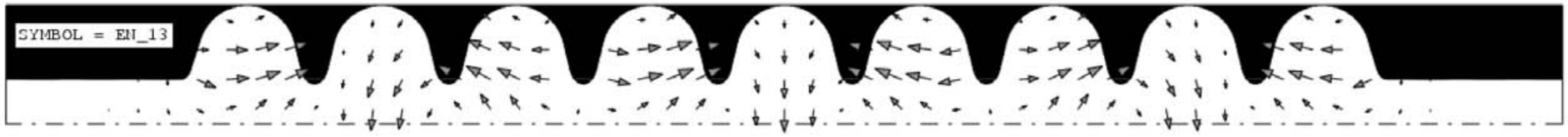
mode 6 (~6π/9) 1.707 GHz



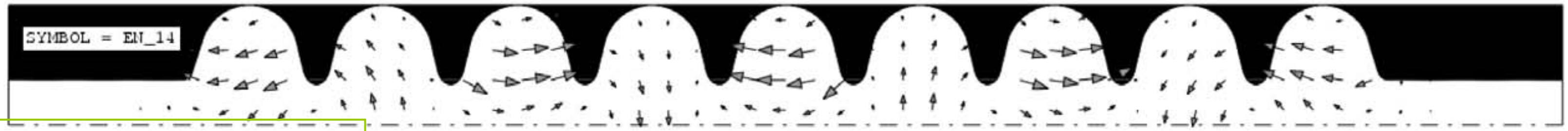
mode 7 (~7π/9) 1.735 GHz



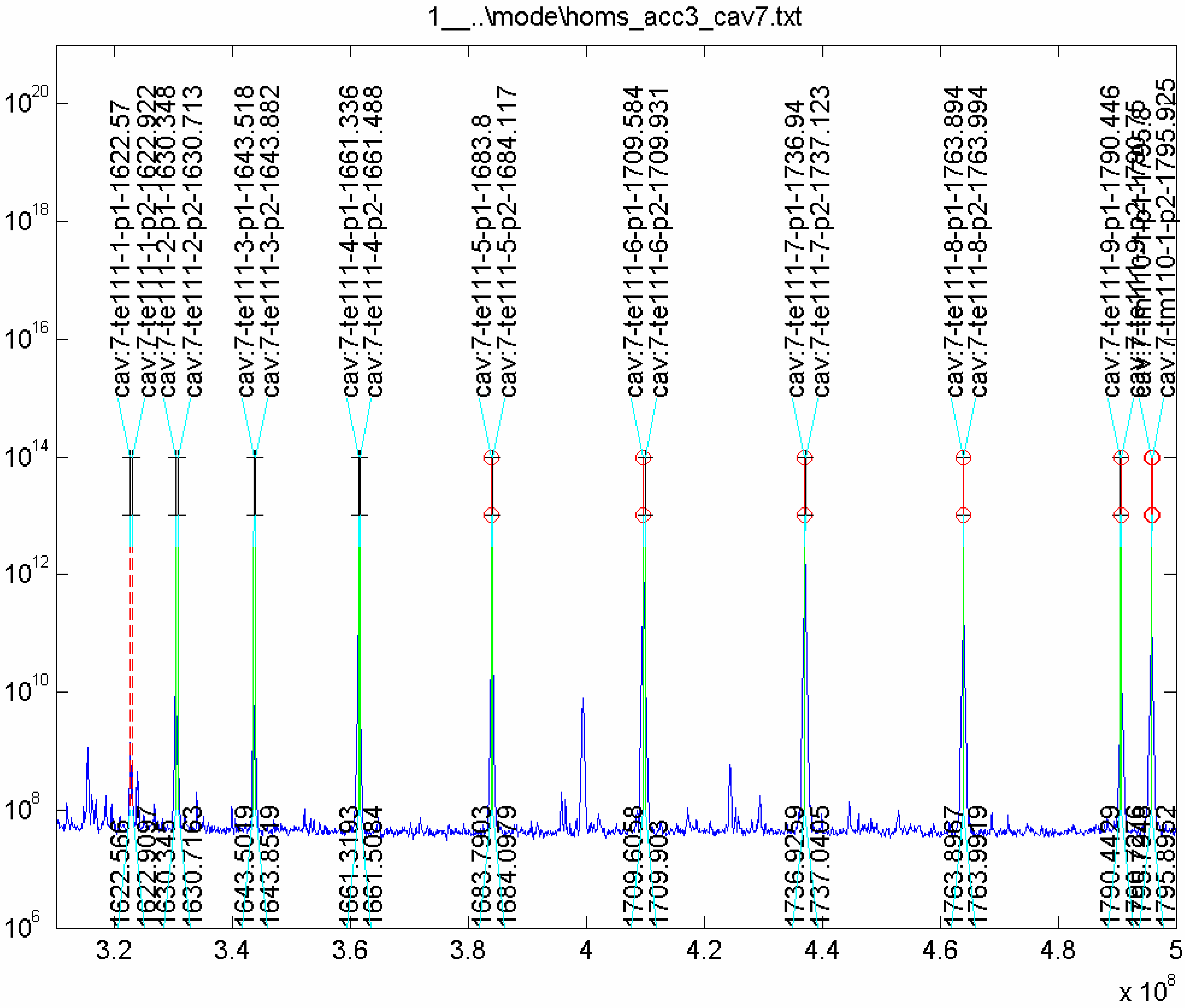
mode 13 (~6π/9) 1.866 GHz



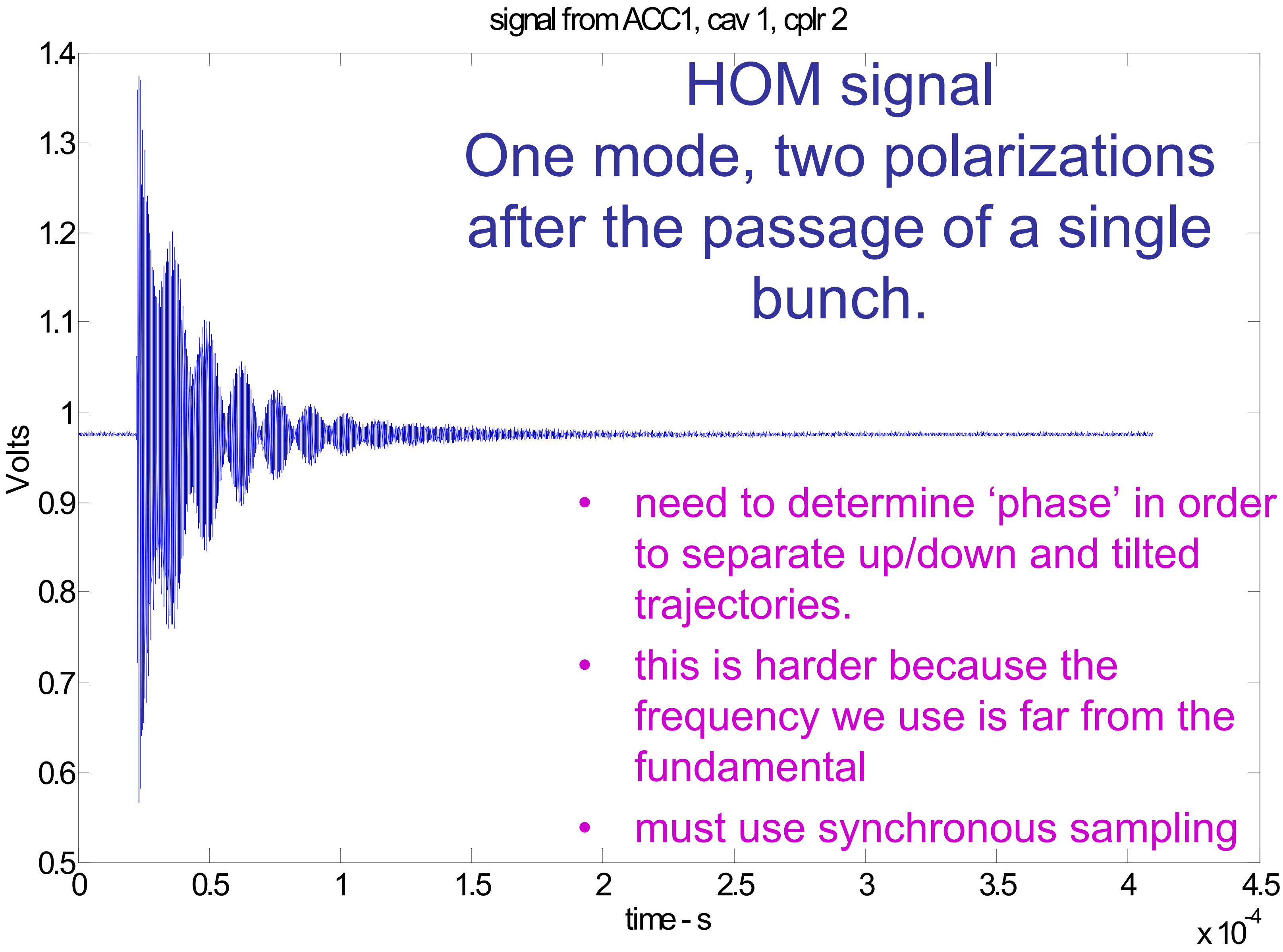
mode 14 (~5π/9) 1.875 GHz



Martin Dohlus - DESY

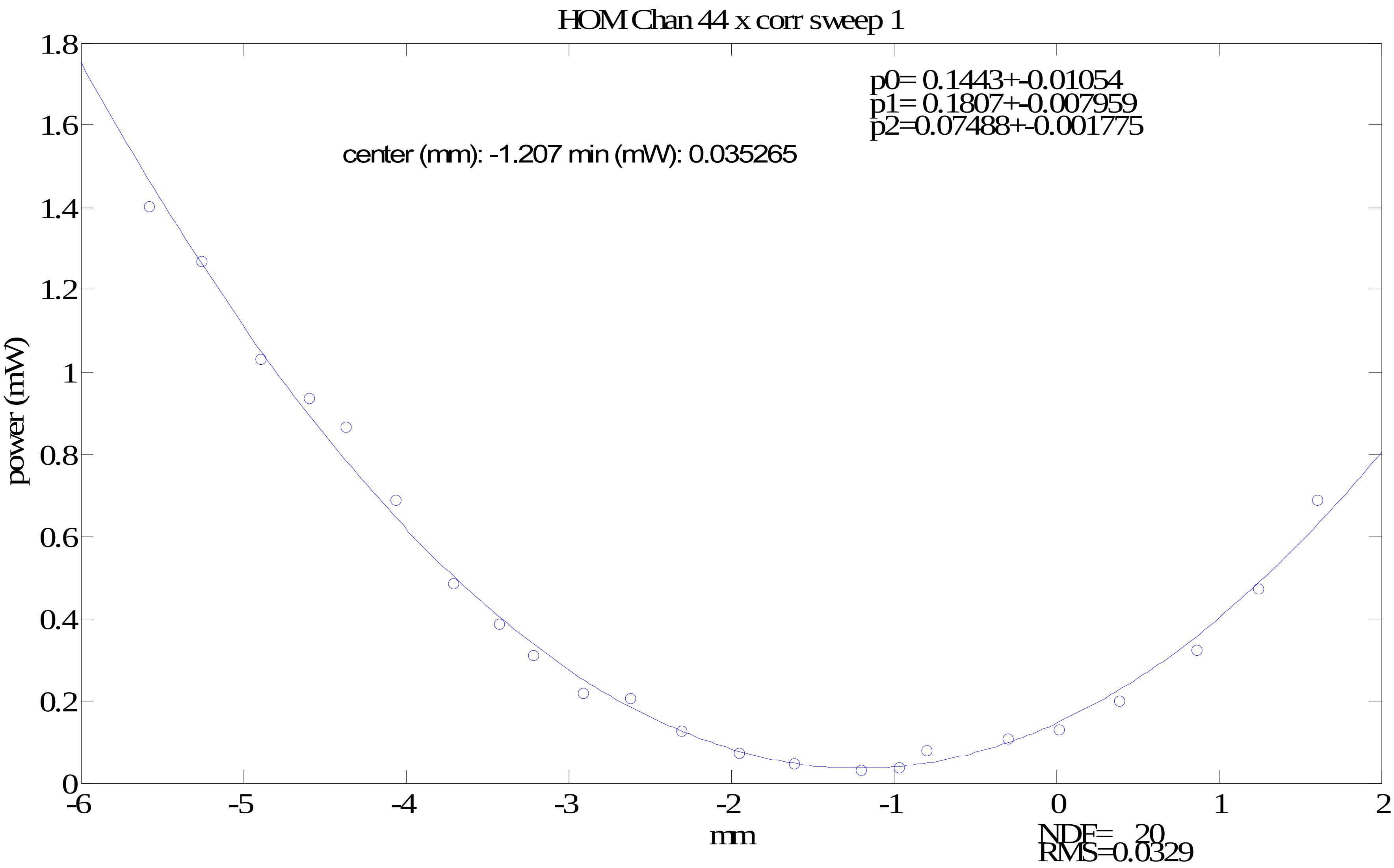

1__..\mode\homs_acc3_cav7.txt
10^20
10^18
10^16
10^14
10^12
10^10
10^8
10^6
3.2
3.4
3.6
3.8
4
4.2
4.4
4.6
4.8
5
x 10^8
cav:7-te111-1-p1-1622.57
cav:7-te111-1-p2-1622.922
cav:7-te111-2-p1-1630.348
cav:7-te111-2-p2-1630.713
cav:7-te111-3-p1-1643.518
cav:7-te111-3-p2-1643.882
cav:7-te111-4-p1-1661.336
cav:7-te111-4-p2-1661.488
cav:7-te111-5-p1-1683.8
cav:7-te111-5-p2-1684.117
cav:7-te111-6-p1-1709.584
cav:7-te111-6-p2-1709.931
cav:7-te111-7-p1-1736.94
cav:7-te111-7-p2-1737.123
cav:7-te111-8-p1-1763.894
cav:7-te111-8-p2-1763.994
cav:7-te111-9-p1-1790.446
cav:7-te111-9-p2-1790.75
cav:7-tm110-1-p1-1795.8
cav:7-tm110-1-p2-1795.925
1622.566
1622.9097
1630.345
1630.7163
1643.5019
1643.8519
1661.3193
1661.5084
1683.7903
1684.0979
1709.6058
1709.903
1736.9259
1737.0405
1763.8987
1763.9919
1790.4429
1795.8952

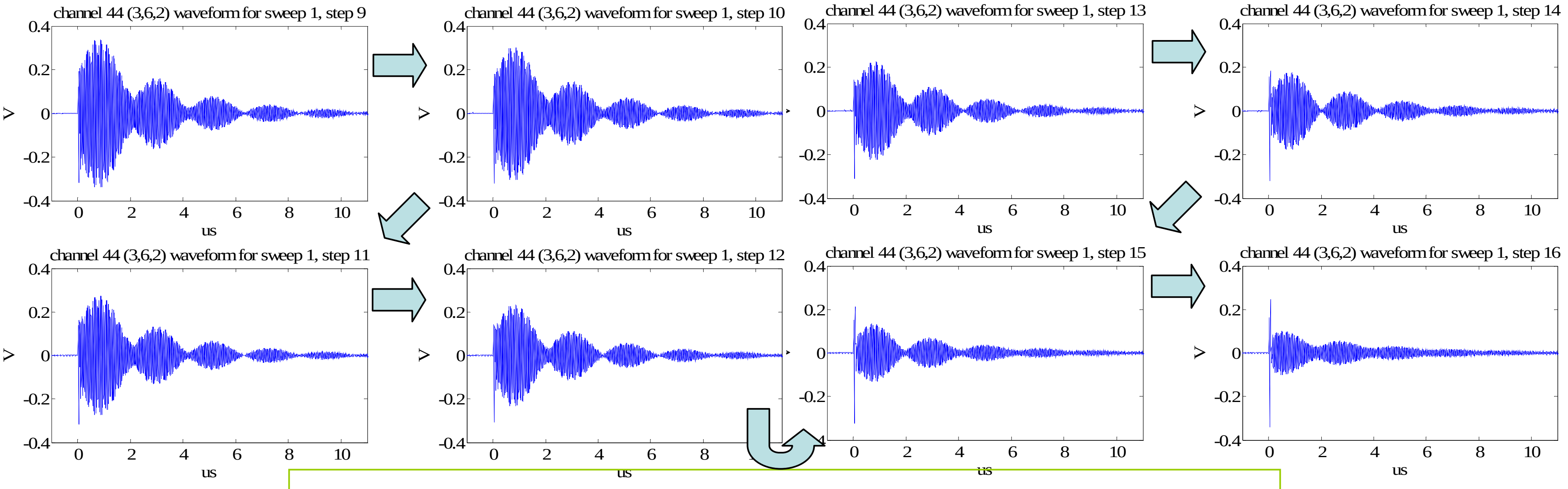
HOM signal One mode, two polarizations after the passage of a single bunch.



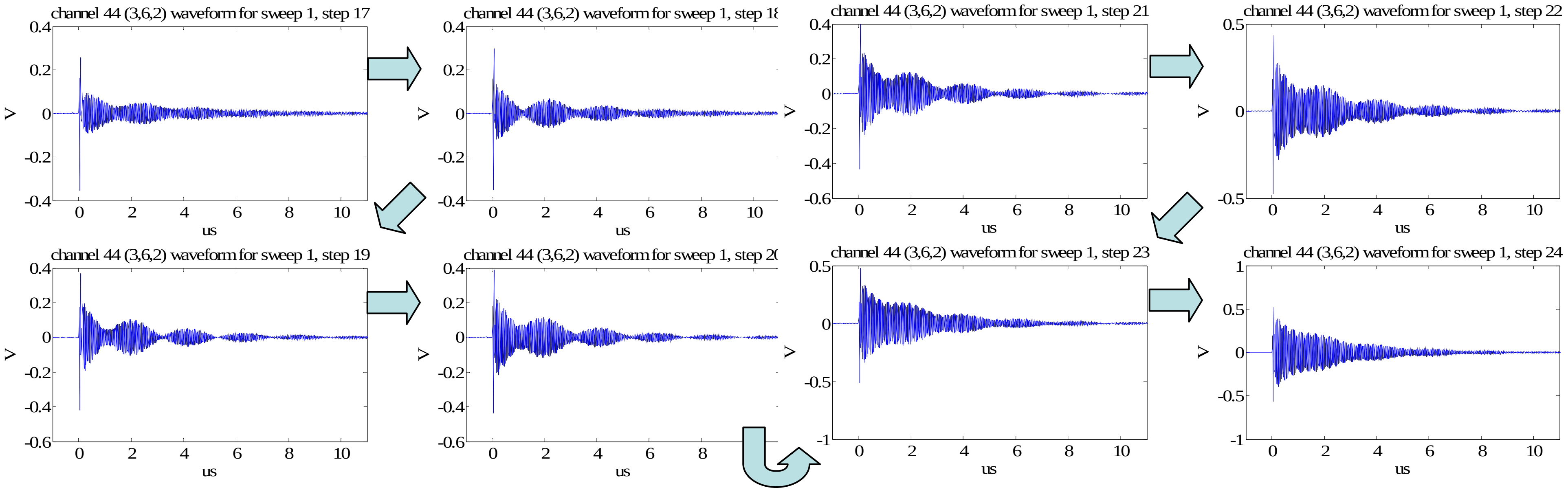
- need to determine ‘phase’ in order to separate up/down and tilted trajectories.
- this is harder because the frequency we use is far from the fundamental
- must use synchronous sampling

Close up of one ACC3 power sweep: (mW vs mm)



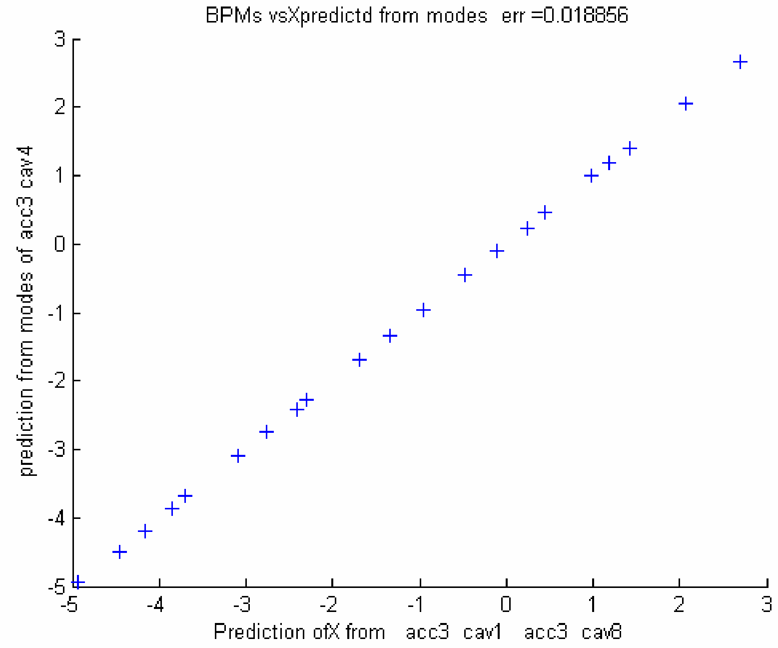


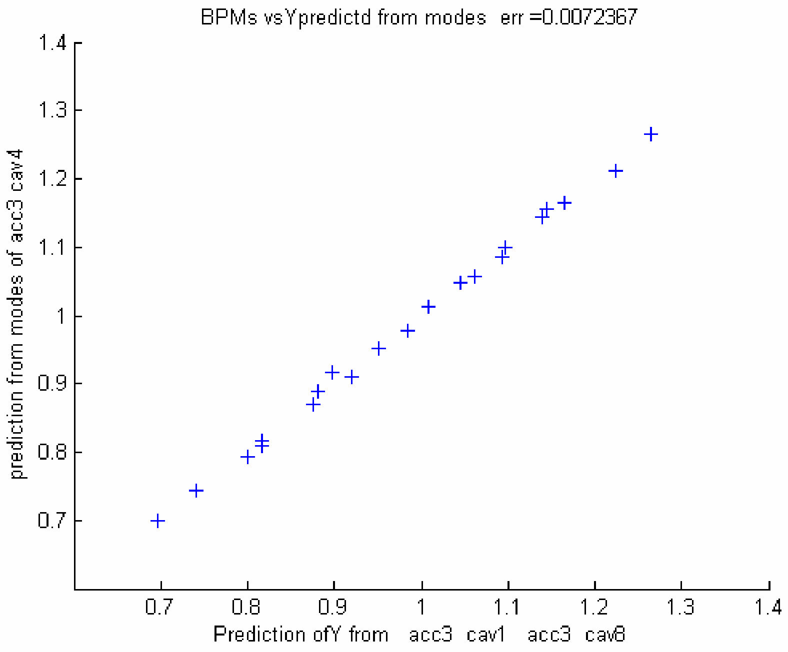
Sequence of HOM signals vs trajectory…



Compare prediction of “X” and “Y” from cavities 1 and 8 with cavity 4

- calibrate using correctors – the cryomodule does not have cavity ‘movers’
- the cavity is an excellent BPM – after the calibration process is done

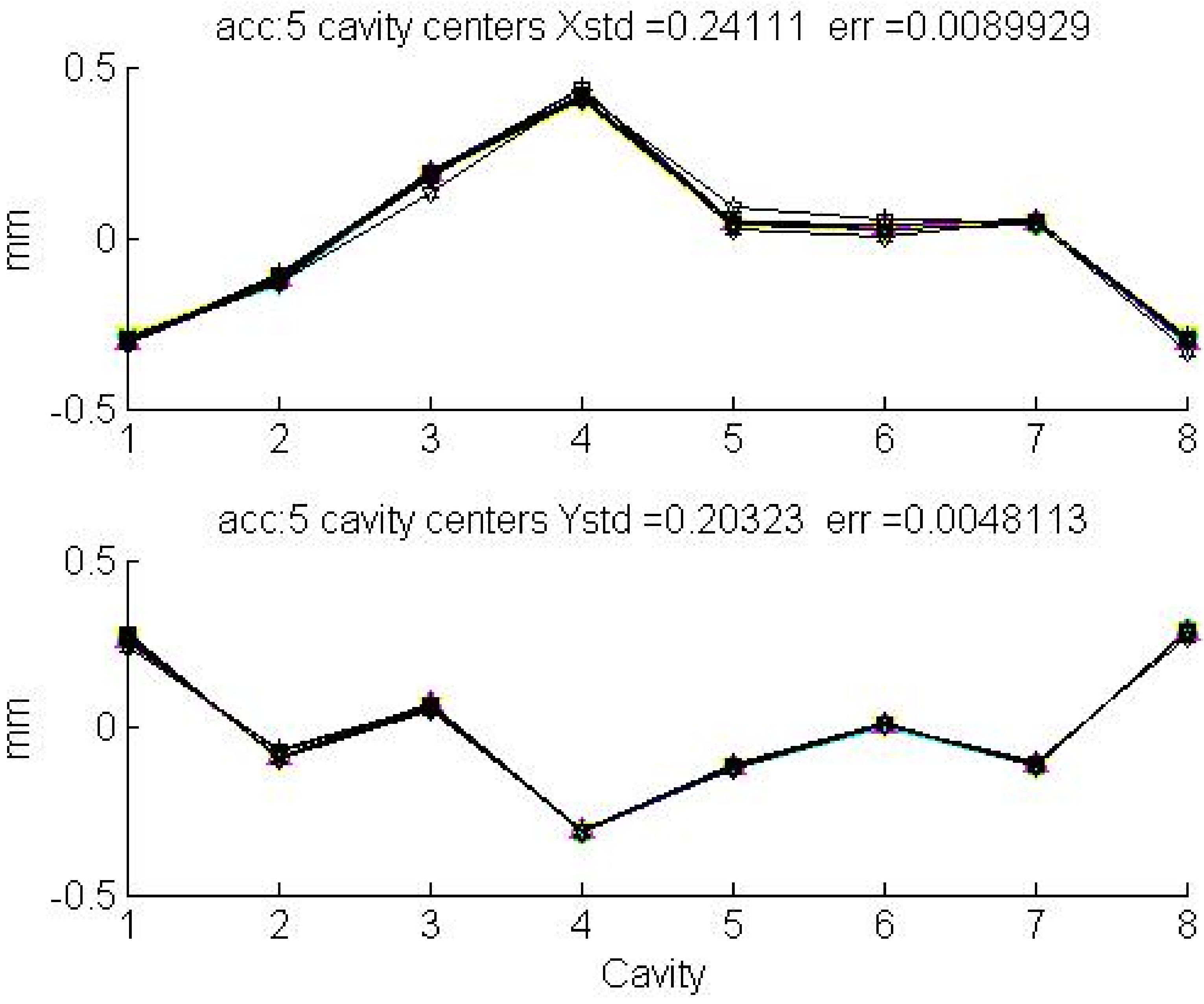




18 microns RMS from 8 mm motion X
7 micron RMS from 700 micron motion Y

Uses of HOM Monitors

- TTF – VUVFEL: roughly triple the number of position monitors
  - High precision trajectory studies possible
- Finding the centers of the cryo-cavities
- Understanding cavity construction
  - Broad band (all 18 modes, expensive)
  - Narrowband (one strong mode, inexpensive)
- Monopole modes (2^{nd} passband ~2500MHz) for precise LLRF phasing
- Remove the need for a separate linac BPM system



acc:5 cavity centers Xstd =0.24111 err =0.0089929

acc:5 cavity centers Ystd =0.20323 err =0.0048113

Uses of Beam Position Monitors

- Testing particle beam optics & controlling emittance growth
- Finding sources of instability
  - SLAC Linac beam pulse to pulse oscillations → driven by mechanical support resonances (7Hz)
  - Vibrations (driven by 60 nm p/p ground motion) – have p/p amplitude of 50 um

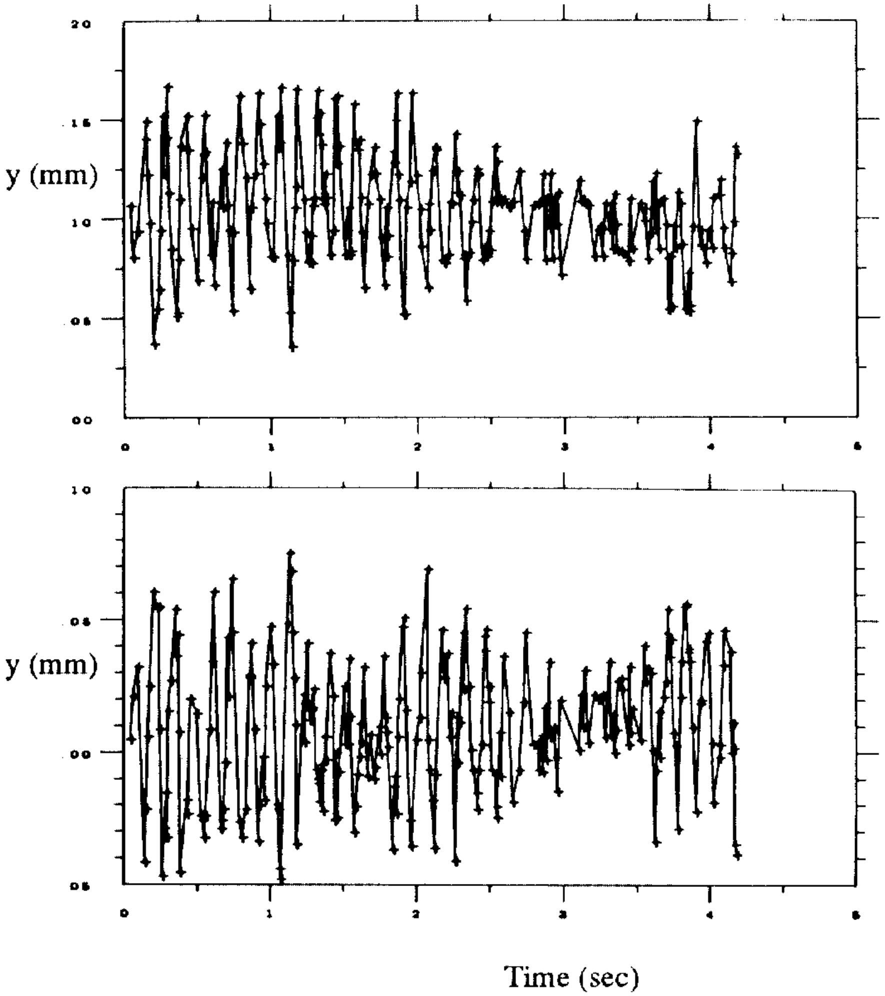


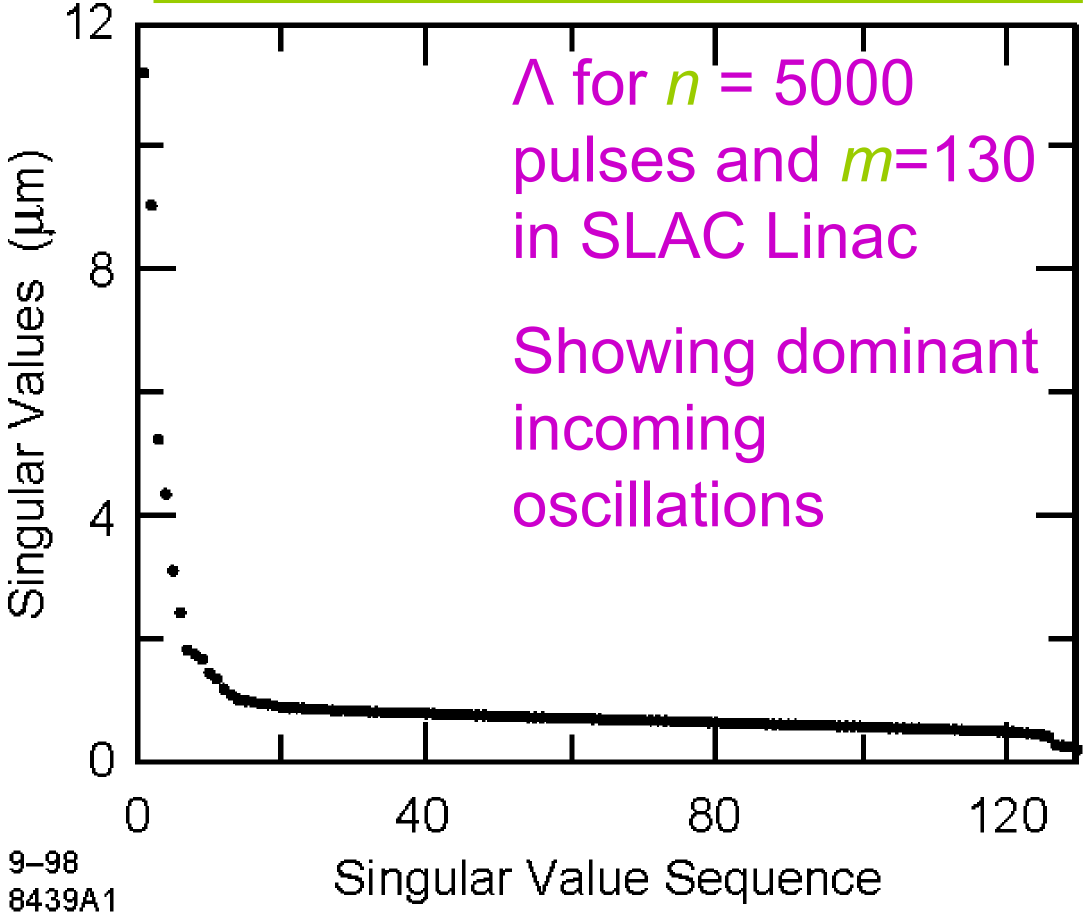
Figure 1 Observed positron vertical beam oscillations on

Linear Algebra using large numbers of BPM's

- 'Model Independent Analysis'
- a set of BPM readings from *m* BPM's and *n* pulses forms a *mxn* matrix *B* which can be decomposed using *Singular Value Decomposition*:
- "Eigenvectors in U and the eigenvectors in V form two complete bases respectively for the temporal space and the spatial space spanned by the underlying physical changes"
- Λ is a diagonal matrix of eigenvalues indicating the relative strength

$$B = U\Lambda V^T$$

Reference 3, Numerical Recipes

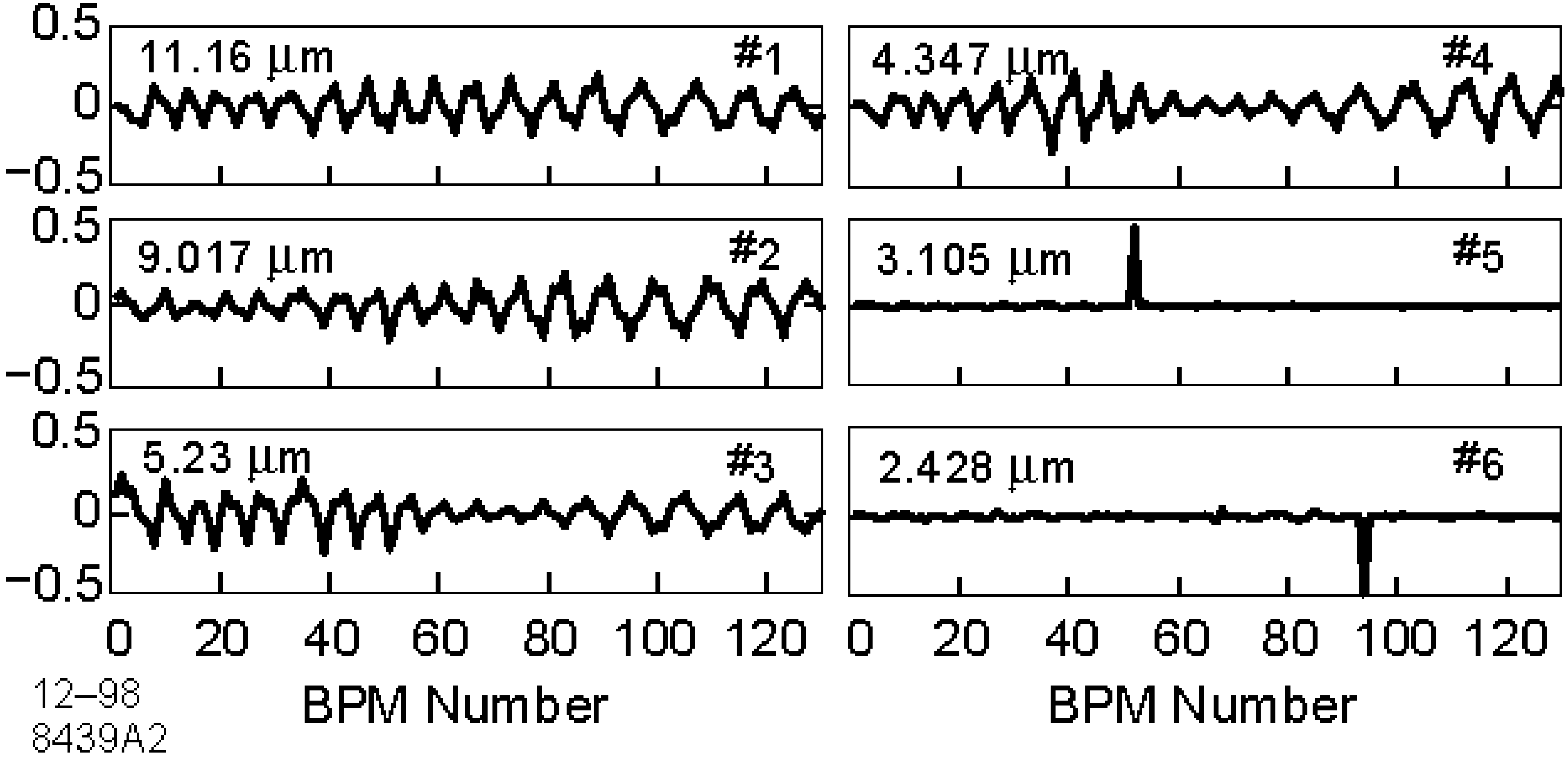


Λ for *n* = 5000 pulses and *m*=130 in SLAC Linac

Showing dominant incoming oscillations

Spatial – first 6 - ‘eigenvectors’ showing largest modes

- Sine-like & cosine-like components
- Can also include other devices in *B* to select correlations



Challenges with BPM’s

- Direct interaction of the cavity or stripline structure with the beam particles
  - Electromagnetic showers
  - Secondary emission
- Mechanical damage
  - Heating by the beam itself or by beam fields
- Non-linearity
  - PEP ‘pin-cushion’ example
- Calibration & Stability…
  - movers and redundancy
- Integration (how it fits in) and cryogenic performance
  - how to clean it…

Beam Based Alignment & Cost liability

- Accelerator design and cost is directly related to required component precision and complexity
- Using a 'pilot' beam and well understood BPM's we can position components far more accurately than we can with conventional optical survey
- This allows cost savings well beyond the value of the BPM system but…
  - We must be sure that system will work properly…
  - RD with 'precision' low emittance beams
  - Many issues in common with LLRF

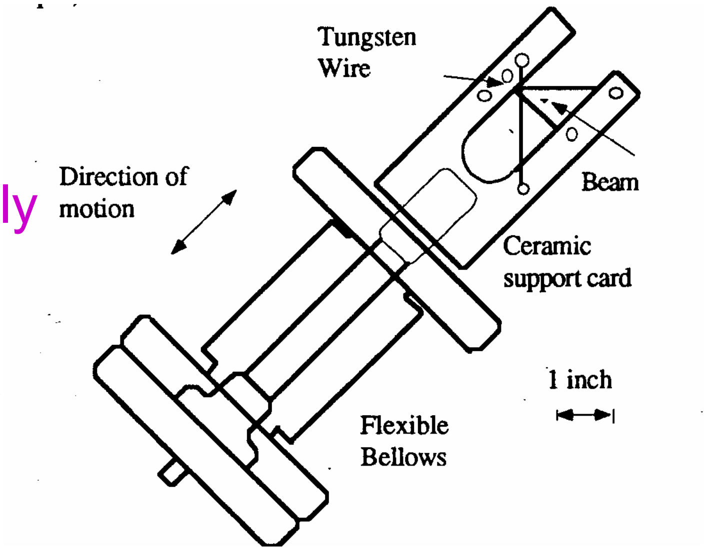
Profile monitors

- Second order: how to measure the size of the beam, tilts, correlations (banana) etc?
- This cannot (?) be done using internal wall currents.
- Must use a *probe* or interaction between the beam and *material/magnetic* field.
- Scanners/samplers vs Imagers
- a kind of 'luminosity' estimate
- ILC linac beam: 10 x 1 x 150
  - think of a flat noodle: 5 x 0.5 x 75 mm
- ILC damping ring beam 200 x 30 x 6000

- Bunch length / temporal structure is much, much, harder than transverse…
  - Microns & nanometers are the frontier & innovation is needed…

Beam transverse profile – scanners:

1. The metallic probe technique: slide a sampling target through →
   - What leaves a print in a target probably breaks the wire
   - basic linear scattering process
   - must have non-biased acceptance for detecting scattered radiation



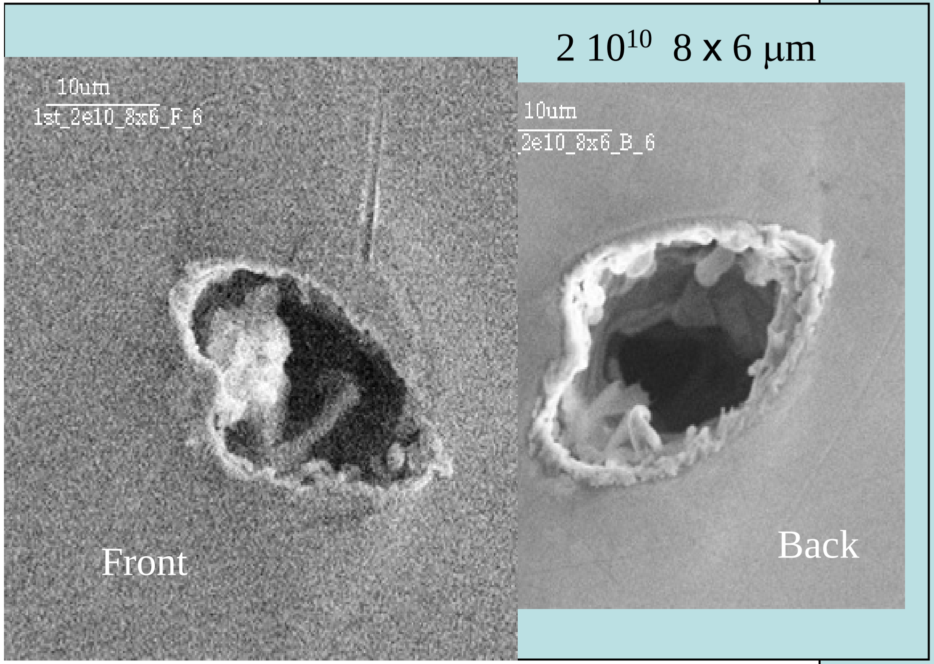
2. The laser probe technique: slide a high power, finely focused beam of photons through the beam
   - (timing, precision, stability, extreme power, detection efficiency,…)

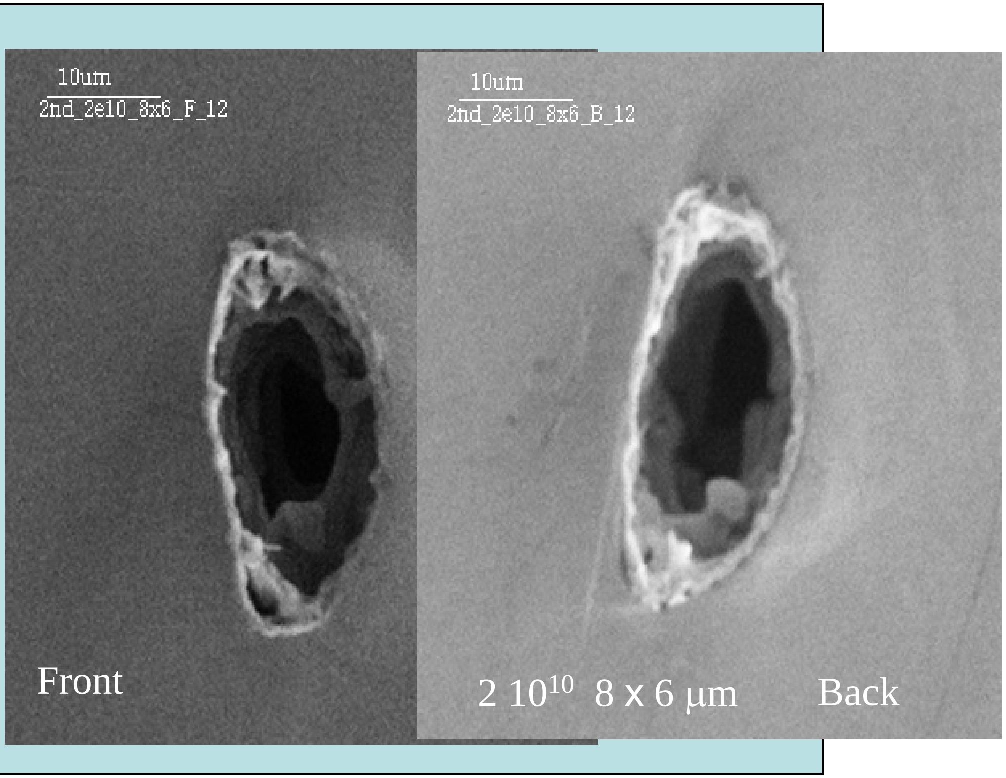
Beam transverse profile – imagers:

1. Optical Transition radiation target / phosphor screen target
   - Limited by material damage threshold – lower than the spoiler damage threshold
   - May work with low intensity single bunches at low energy
2. Synchrotron radiation
   - Beams too small for ‘optical’ monitors
   - X-ray systems required

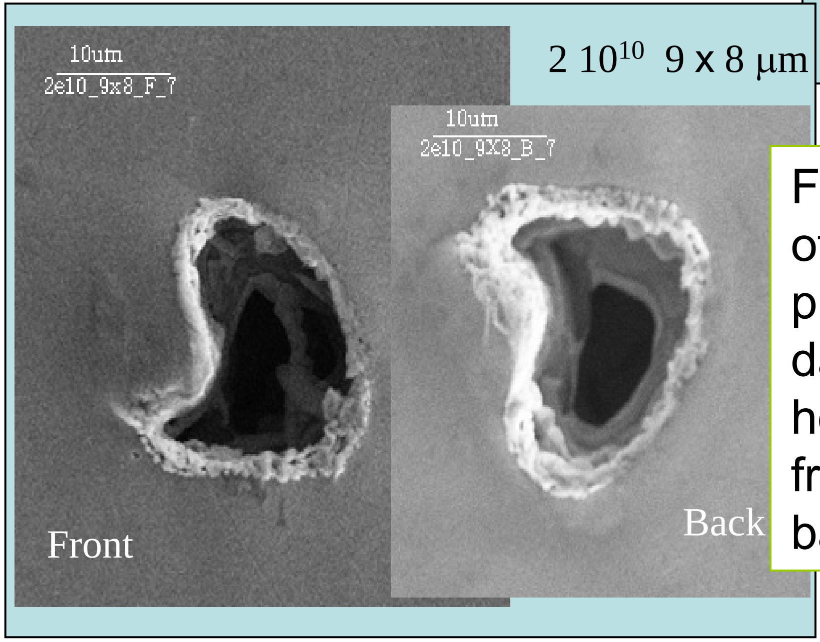
- ILC will have all 4 types of above profile monitors
  - Others also probable

FFTB Single Pulse Damage Coupon Test - front and back side - same scale

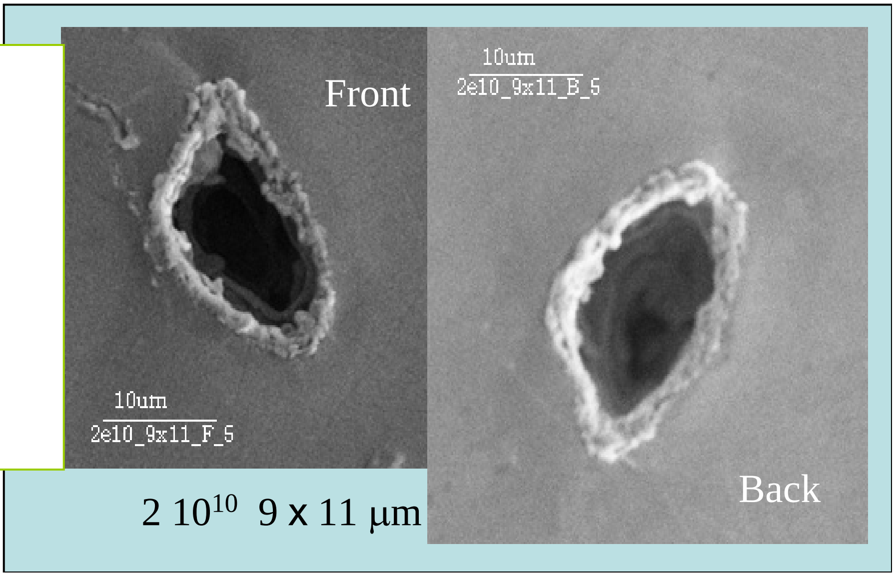

2 10^{10} 8 x 6 µm



2 10^{10} 8 x 6 µm


2 10^{10} 9 x 8 µm

Four pairs of single pulse damage holes→ front and back



2 10^{10} 9 x 11 µm

Specifying Profile Monitor Performance

- Critical performance characteristics:
  - minimum measurable beam size (dynamic range – spatial)
  - resolution (measurement reproducibility for a given beam)
  - intensity range
  - accuracy – systematic error
    - emittance is related to σ^2 so error control is critical
  - data rate
- How hard is it to find the beam?
- What is the smallest feature?
  - beams are often NOT gaussian

Specifying Profile Monitor Performance (2)

- x ←→ y coupling limitations
  - interference from x in the y measurement
  - extreme aspect ratios in the bunch compressor, BDS.

- Data rate
  - images at the bunch rate? (3 to 6 MHz)
  - sample spacing → 5/sigma
  - 50 samples needed for a ‘profile’… 10 seconds at ILC

Measuring emittance → the predictor of luminosity

$$\varepsilon_y^2 = \sigma_y^2 \sigma_{y'}^2 - \sigma_{yy'}^2$$

$$= \sigma_{11}^2 \sigma_{22}^2 - \sigma_{12}^2$$

more than one monitor / more than one beam optics is required for an 'emittance' measurement

(no real correlation $\sigma_{yy'}$ or angular divergence $\sigma_{y'}$ monitor available for high energy beams)

Online measurement: use a set of profile monitors (min 3 for zero constraint)

Optics must provide y' and yy'

Again a difference of large numbers

Measurements of energy spread require dedicated systems with dispersion information

Measuring emittance:

$$R = \begin{bmatrix} R_{11} & R_{12} \\ R_{21} & R_{22} \end{bmatrix}$$

$$\boxed{\sigma_{beam} = \sqrt{\sigma^{i}}}$$

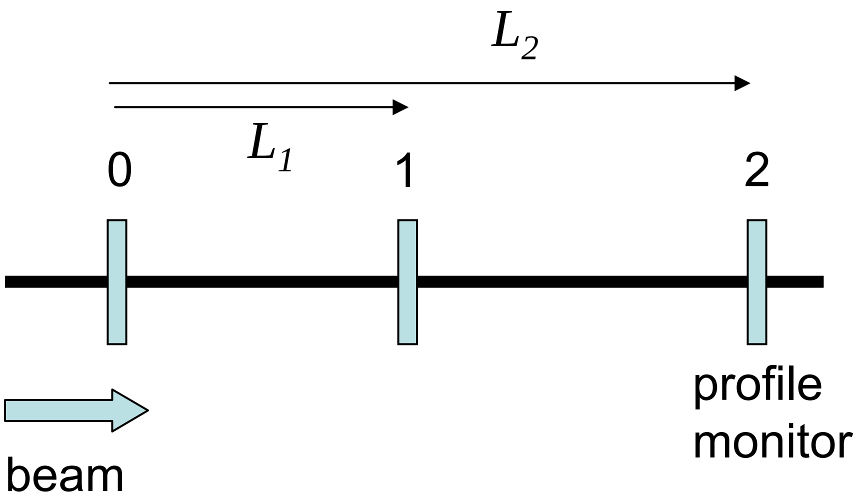
$$\sigma^{1} = R\sigma^{0}R^{T}$$

$$\sigma_{11}^{1} = R_{11}^{2}\sigma_{11}^{0} + 2R_{11}R_{12}\sigma_{12}^{0} + R_{12}^{2}\sigma_{22}^{0}$$

In a ‘drift’ space, with no focusing elements:

$$R_{L} = \begin{bmatrix} 1 & L_{1} \\ 0 & 1 \end{bmatrix}$$

$$\boxed{\sigma_{11}^{1} = \sigma_{11}^{0} + 2L_{1}\sigma_{12}^{0} + L_{1}^{2}\sigma_{22}^{0}}$$



Imagers

$$d \geq \frac{\lambda}{\theta}$$

- Diffraction:
  - ILC transverse beam dimensions are close to ‘optical wavelength’
  - for $\sigma \approx \lambda$ we must have:

$$f\# \approx 1$$

  - synchrotron radiation has it’s own aperture → 1/gamma
  - d is the size observed, lambda is the wavelength and theta is the useful opening angle
- Depth of field
- image rate

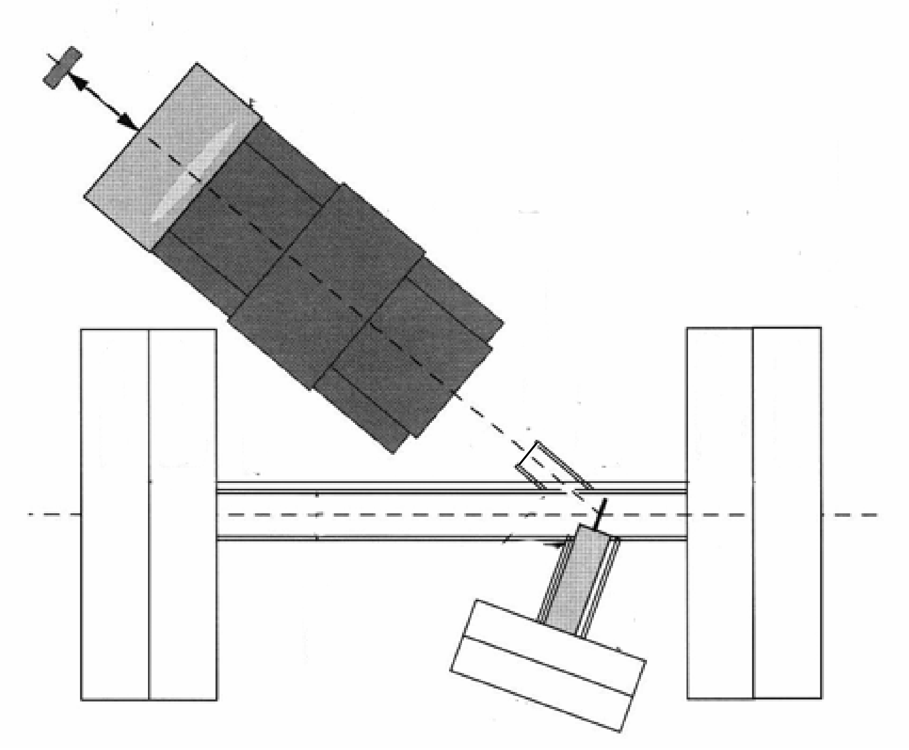
Transition Radiation

- Transition radiation is produced when a relativistic particle traverses the boundary between materials of different electrical properties. Even though our beams are small, this is predominantly an incoherent effect. We can image the radiation to estimate beam size.
  - Broad spectrum
  - wide opening angle for high energy beams
  - most of the energy is with 1/gamma
  - (exponential for synchrotron light)

$$W \propto {}^{1}\!/_{\theta^2}$$

Transition radiation profile monitor:

- like a ‘mirror’ that reflects the fields of the beam particles at the angle of specular reflection
- depth of field is a problem because the image source is not normal to the optical axis
- microscope objectives have close to f#=1 performance but have limited range and must be mounted very close to the beam
- vacuum window interferes with objective optics



Synchrotron Radiation

- Synchrotron radiation is emitted when charged particles traverse a curved path.
  - we can think of the particle being separated from its flat ‘pancake’ field
- the critical frequency is defined as being centered in the energy spectrum
- opening angle sig_θ grows weakly for long wavelengths
  - (approximation for long wavelengths)
  - nominal critical energy opening angle 1/gamma
- intensity (I) falls weakly for long wavelengths

$$\varepsilon_c = \frac{3}{2}\hbar c \,{}^{\gamma^3}\!\!/_{\rho}$$

$$\varepsilon_c(\mathrm{keV}) = 0.66E(\mathrm{GeV})^2 B(\mathrm{T})$$

$$\sigma_\theta E \cong \frac{0.5}{\left({}^{\omega}\!/_{\omega_c}\right)^{1/3}}$$

sig_θ – mrad
E - GeV

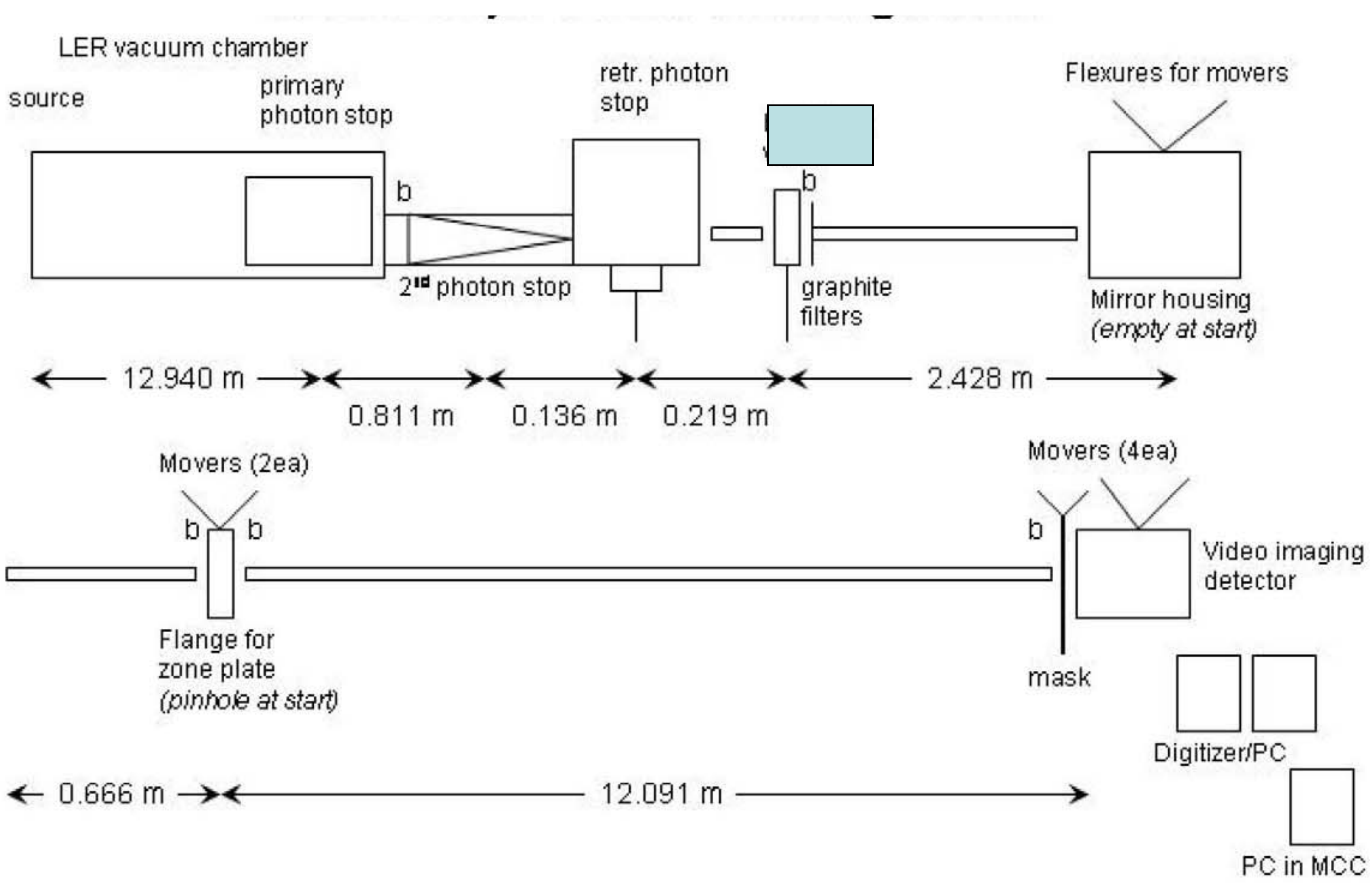
$$I \propto \left({}^{\omega}\!/_{\omega_c}\right)^{1/3}$$

Imaging synchrotron radiation from damping rings→ X-ray imaging

- pinhole for >10 um
- zone plates to below 1 um
  - monochromator required for both; finer needed for zone plate
  - monochromator cooling can be hard – done for SR sources but not for 1 um resolution

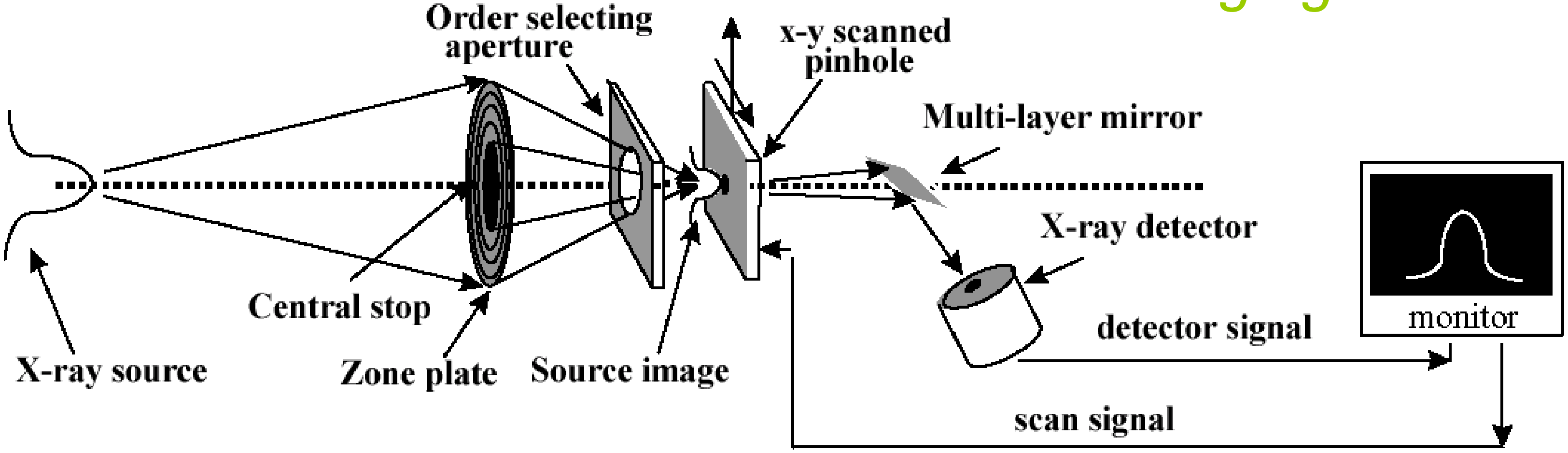
- average power
  - PEP II LER has 1KW/cm^2
  - 4 KeV critical
  - filter or let pass power that will not be used

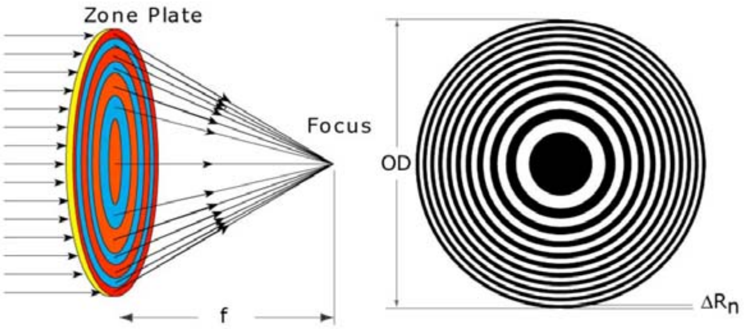
beam line for high power Xray imaging



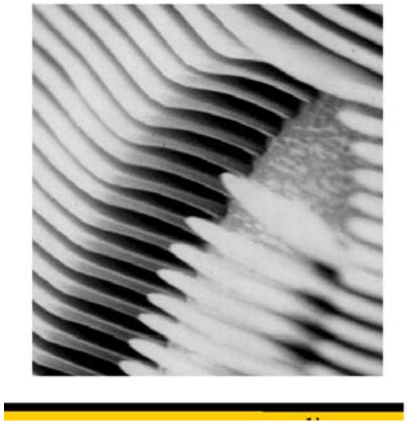
X-ray imaging – Synchrotron Radiation

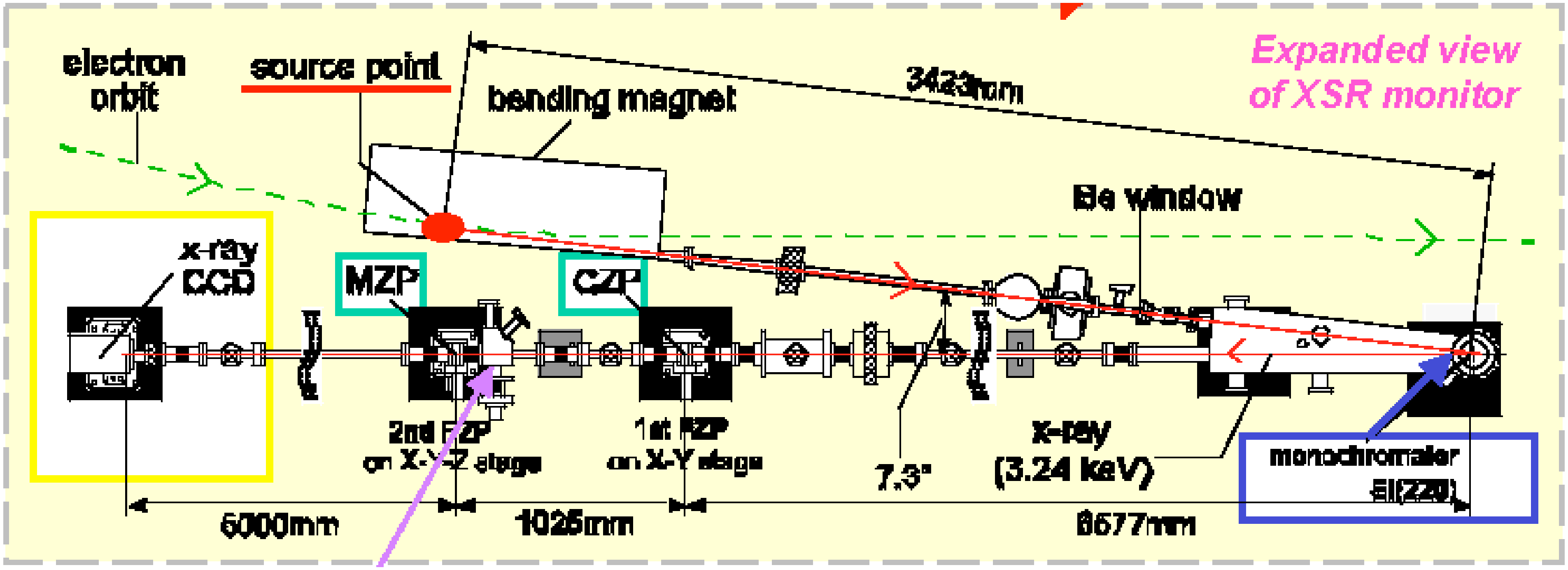
Imaging to ~ 1 um



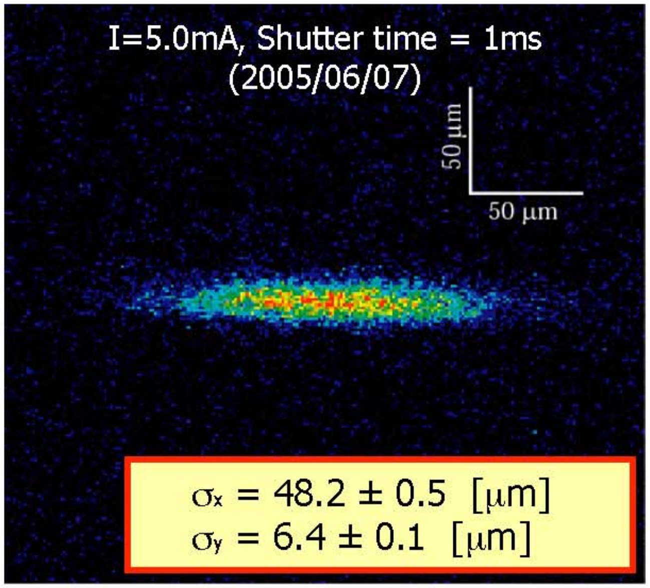


Gold coated Silicon substrate → ~nanometer features. *To 60KeV*
Xradia Corp.



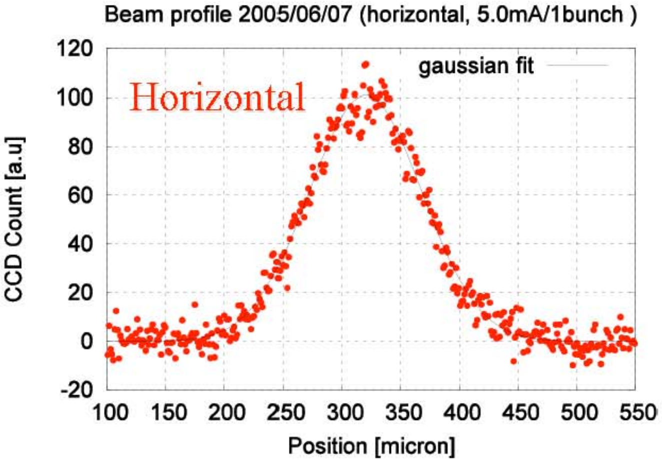

Expanded view
of XSR monitor
electron orbit
source point
bending magnet
3423mm
Be window
x-ray CCD
MZP
CZP
2nd FZP on X-Y-Z stage
1st FZP on X-Y stage
7.3°
X-ray (3.24 keV)
monochromator Si(220)
6000mm
1025mm
8677mm

Example of beam image in ATF DR

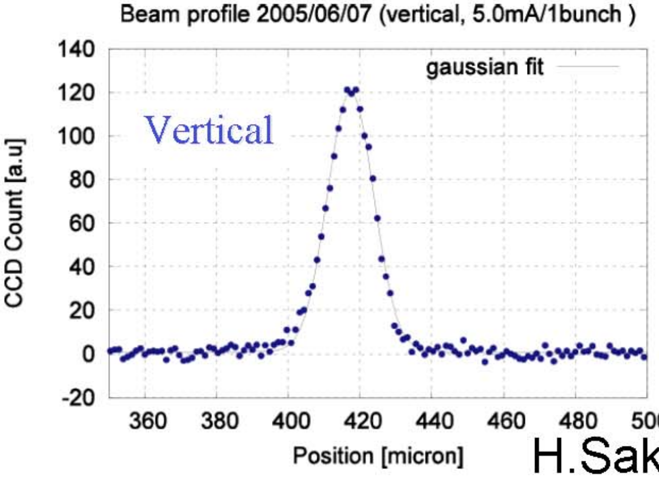


I=5.0mA, Shutter time = 1ms
(2005/06/07)

σ_x = 48.2 ± 0.5 [μm]
σ_y = 6.4 ± 0.1 [μm]



Beam profile 2005/06/07 (horizontal, 5.0mA/1bunch)



Beam profile 2005/06/07 (vertical, 5.0mA/1bunch)

H.Sakai

Real time beam size measurement in ATF for lower emittance tuning.

XSR monitor can be used for ILC damping ring.

Scanning profile monitors:

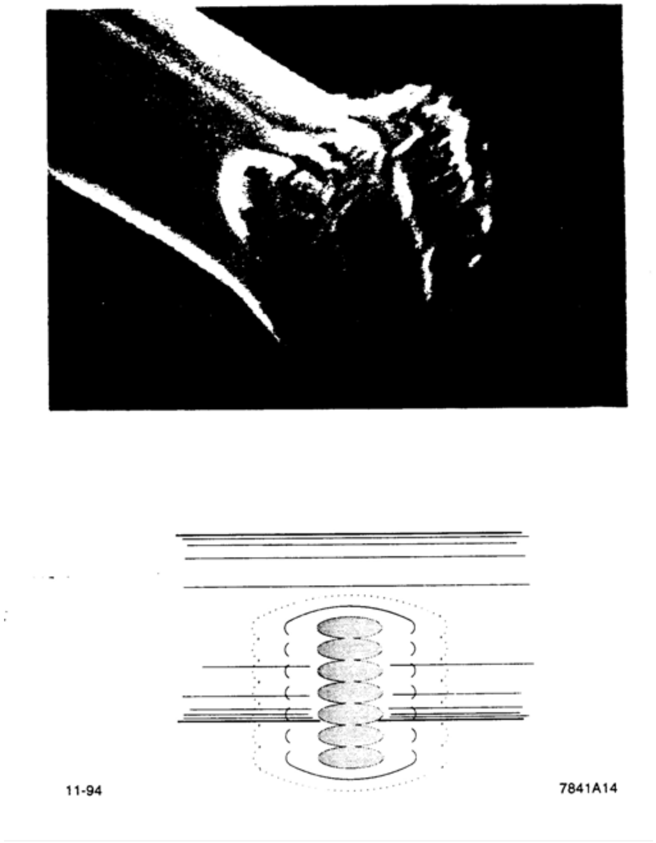
- Sample charge density through a linear scattering & detection process
  - step-by-step / pulse-by-pulse
  - move the beam or move the scatterer
  - probe dimensions should be smaller than the beam

Wire	Laser
interaction:	*interaction*:
thermal, γ /x-rays, δ-rays, secondary emission	Compton, ionization of H$^-$
detection:	*detection*:
radiation, current on wire	radiation, neutralization
Challenge:	*Challenges*:
wire durability / material *	*Technology (integration),* detection

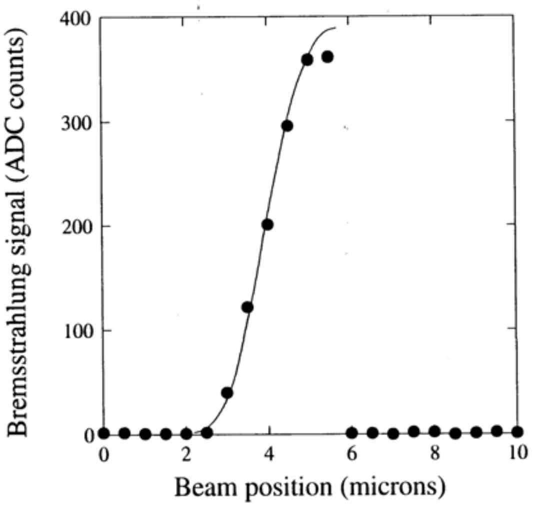
* ILC bunch internal fields can be above atomic binding energies (1V/angstrom)

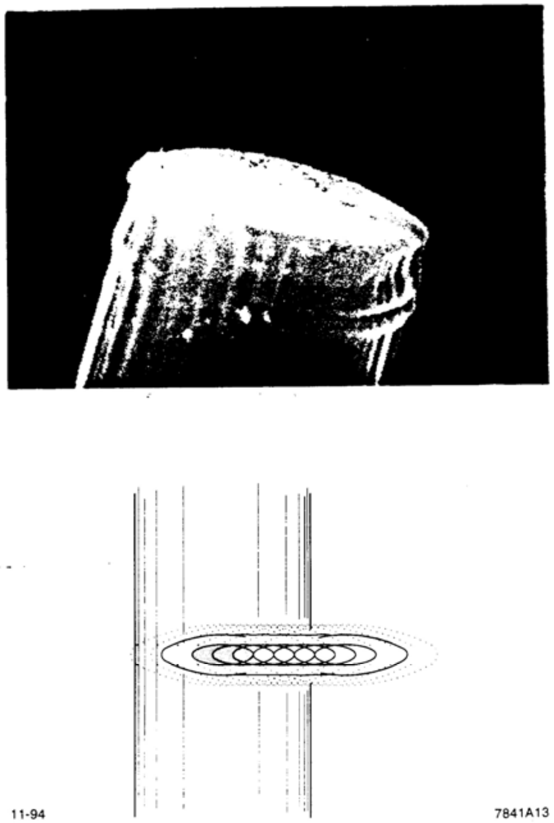
Very small ~ <1 um beams

Two ways to slice a carbon (7um) wire with a flat beam:



The fatal scan:





Laser-based scanner

- For a ring, (~ 100KHz to 1MHz beam passage rate), try interaction with a storage ‘Fabry-Perot’ cavity
  - typical minimum f# ~ 5
  - Gains up to 1000 possible
  - DC and pulsed
- For a transport line, (complex 3 MHz / 5 Hz rate), try a high power laser:
  - f# ~ 1 ← means that σ~λ is possible
  - 10 MW peak, Q-switched cavity – dump
  - 100 MW peak, resonator/regenerative amplifier
- For small beams:
  - interference fringes
  - to λ/20 (30 nm)

Laserwires			
	IP	Laser	Detector
DR	3	3	3
RTML	22	4	6
Linac	20	6	20
BDS	18	6	6
	63	19	35

Laserwire basics:

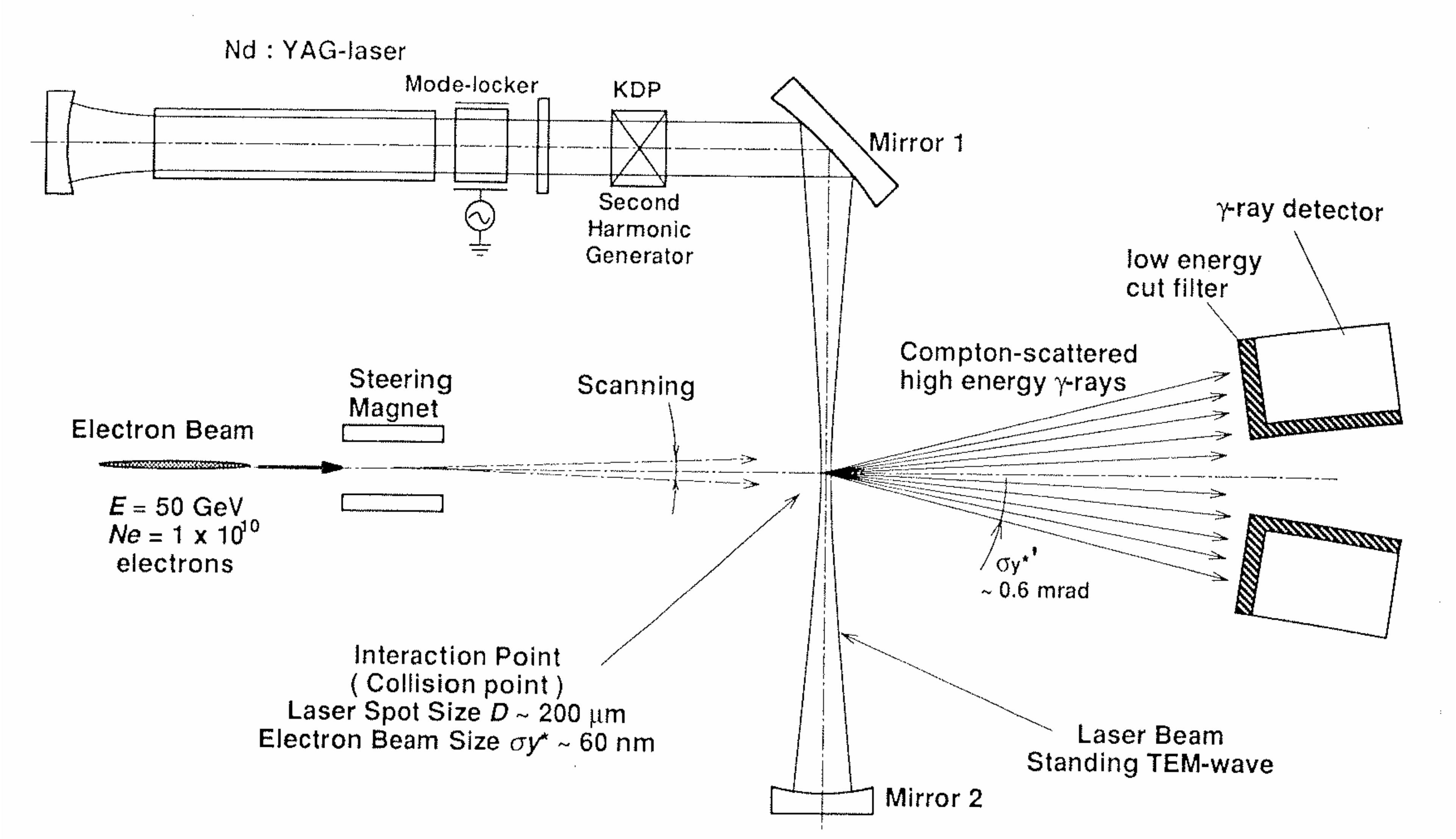
1. Laser (one can feed many IP's)
2. Distribution
3. Deflector (scanner)
4. IP (multi-plane)
5. e/γ Separation
6. Detector

- High power light can fracture vacuum window
  - Likely a 'crack' not really a rupture
  - Must have a protection system near SCRF; technically feasible
- Optical power can increase 'tunnel radiation'
  - Like a wire, have to find the balance between signal and generated radiation
- Hard to integrate into cold system;
  - would need strong testing program to actually make it 'cold'

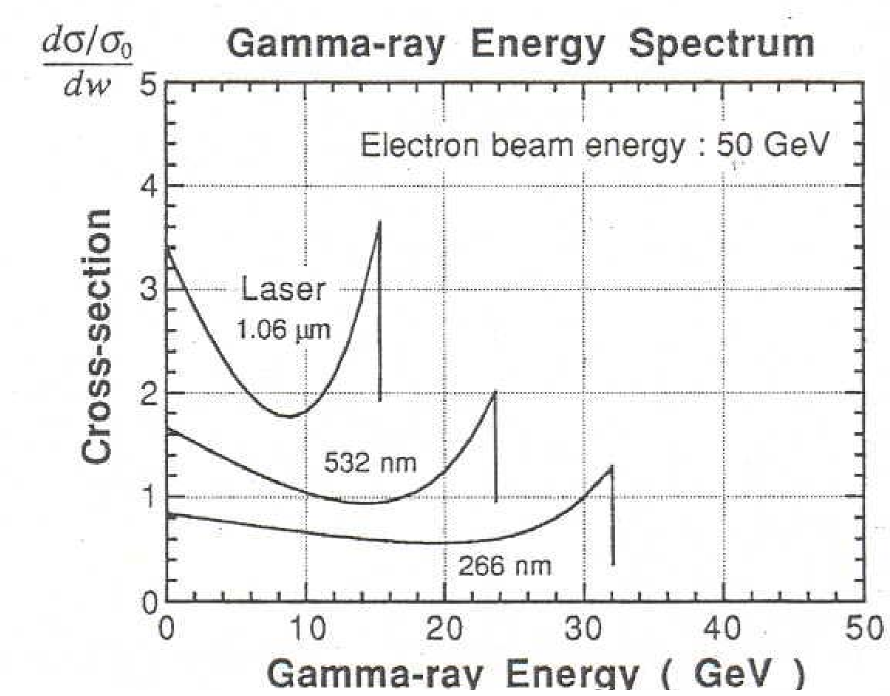
- No intrinsic MPS issues
- Ultra-fast scanning possible

ILC Laserwires

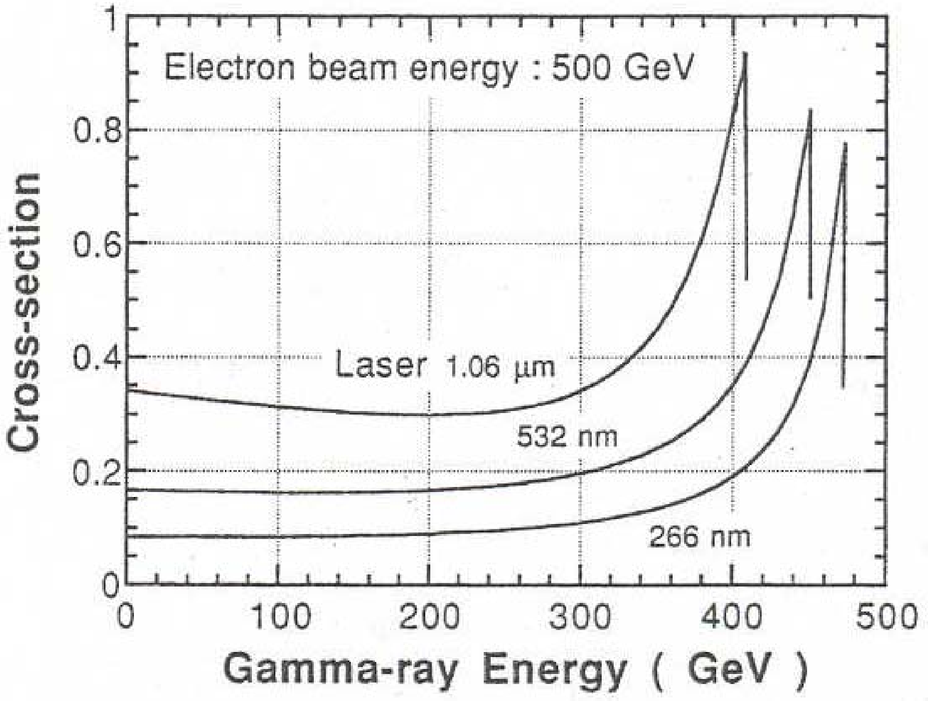
Laserwire components



Laserwire scattered gamma ray spectra:



- the degraded electron spectrum is the reverse
  - 2 body problem



Compton scattering γ- ray Energy ‘endpoint’ for IR and UV lasers

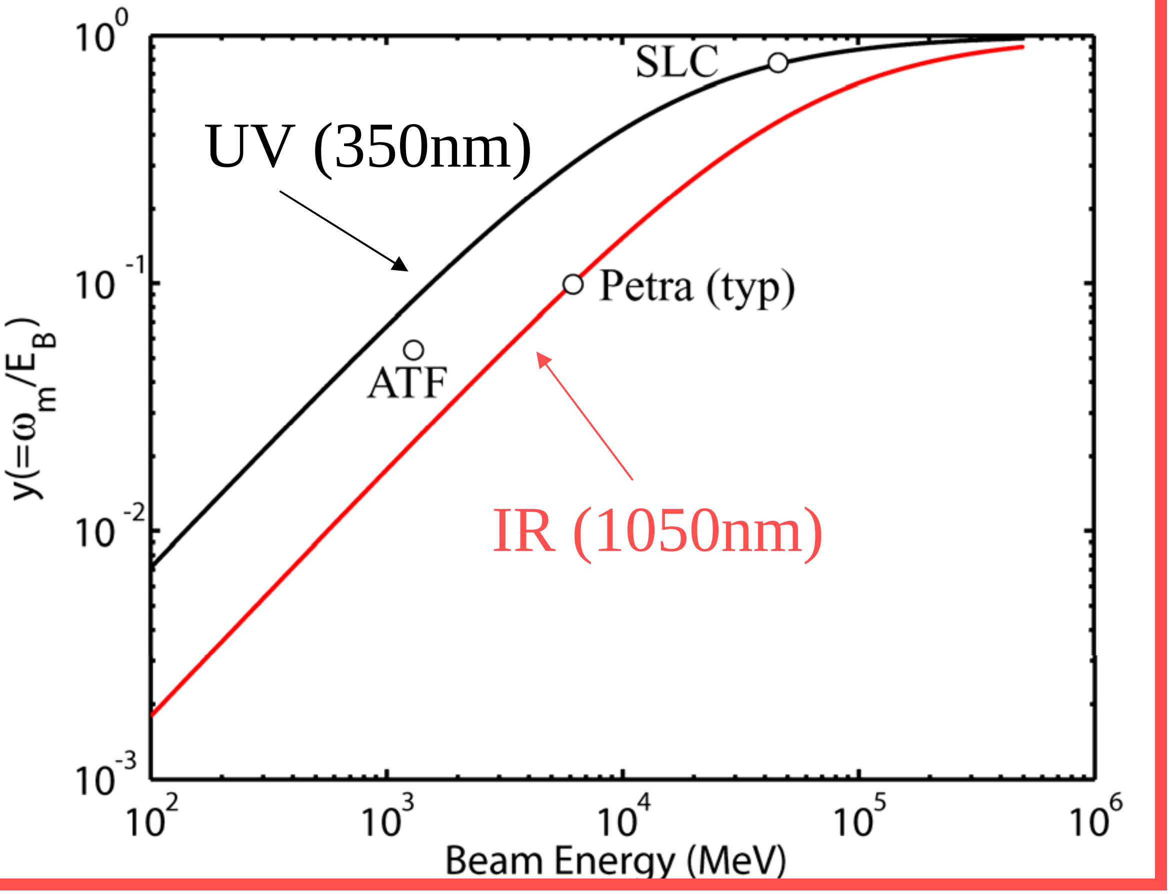
Compton scattered γ-rays are much easier to detect at high energies. Degraded electrons also pushed cleanly outside machine E acceptance for E_beam>~ few GeV.

$$h\nu_{\max} = \frac{2E\varepsilon_1}{1+\varepsilon_1}$$

$$\varepsilon_1 = \frac{\gamma h\nu_0}{m_0 c^2}$$

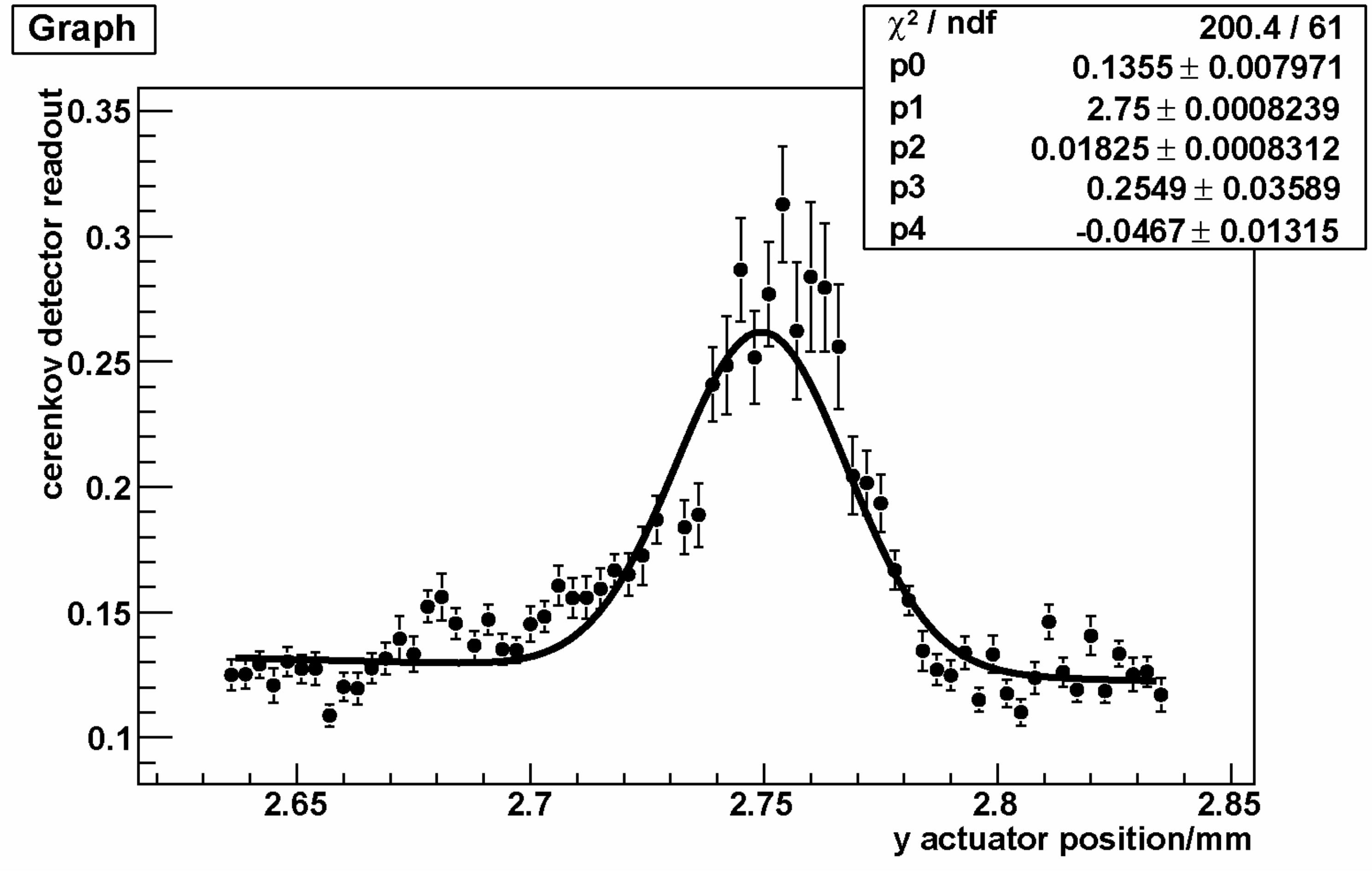
Ref. 8

Normalized g-ray Emax vs E_beam

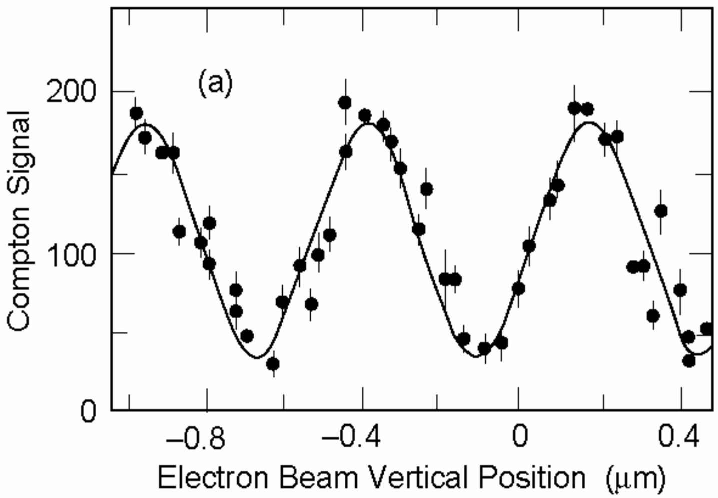


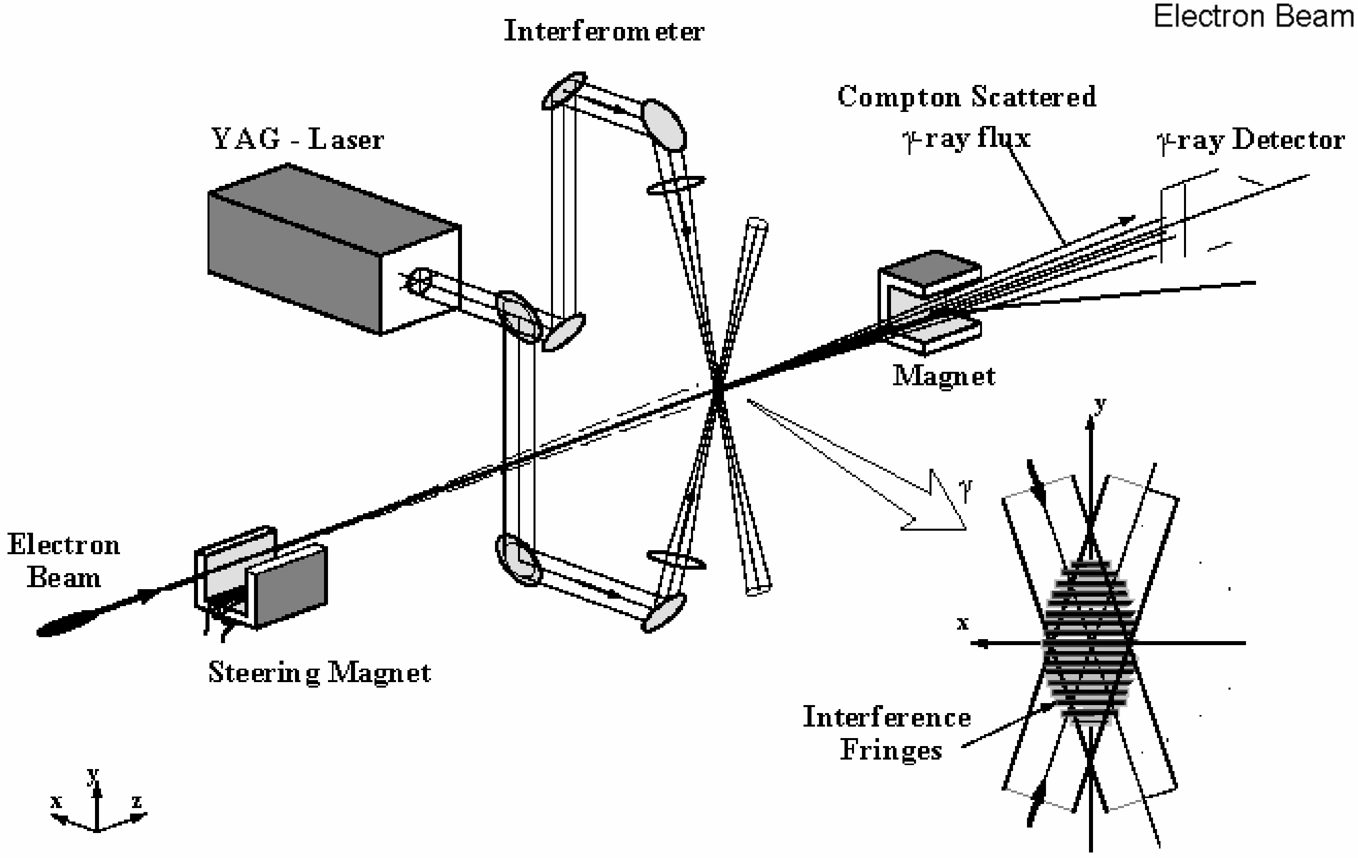
Example laserwire scan from ATF:

- pulsed high power laser with low f# optics

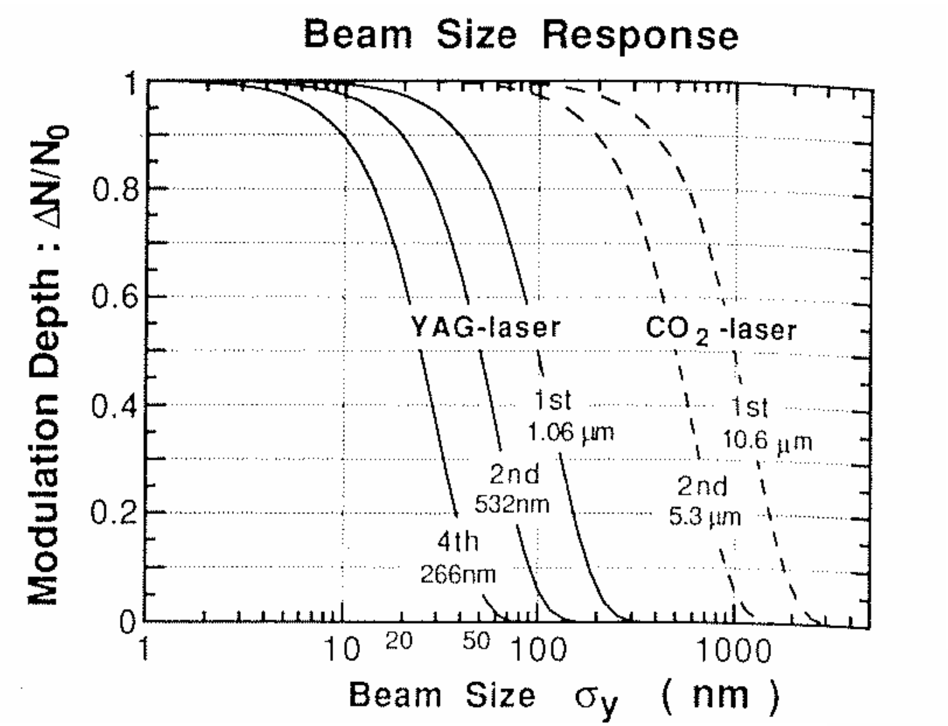


Laser-interference ‘fringe’ profile monitor

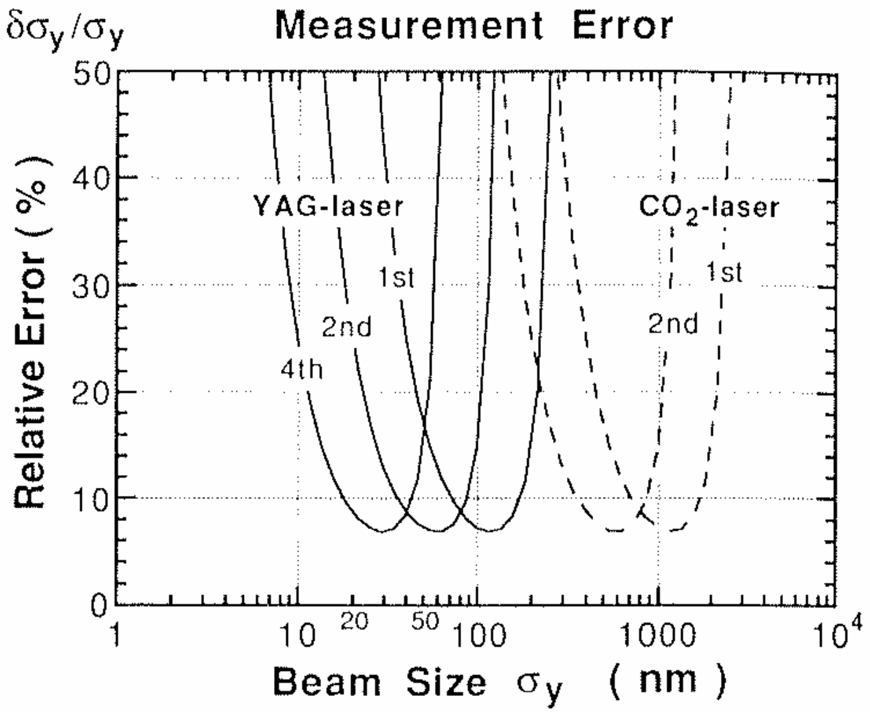




Performance range of ‘fringe’ monitor

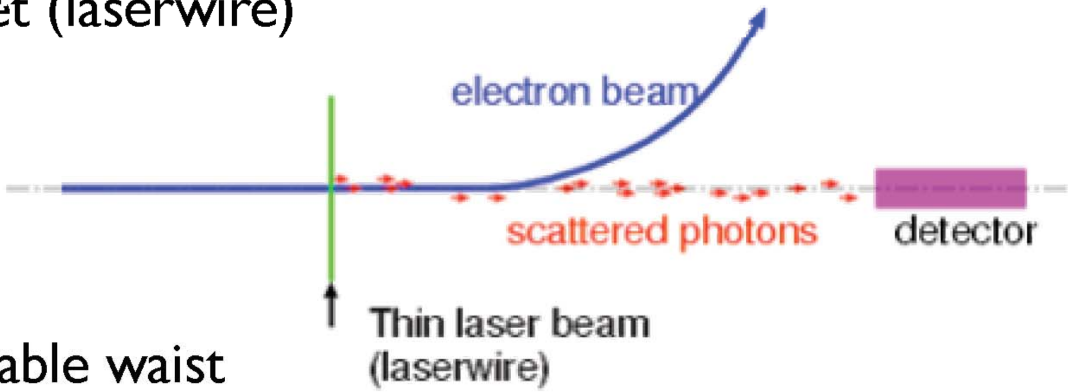


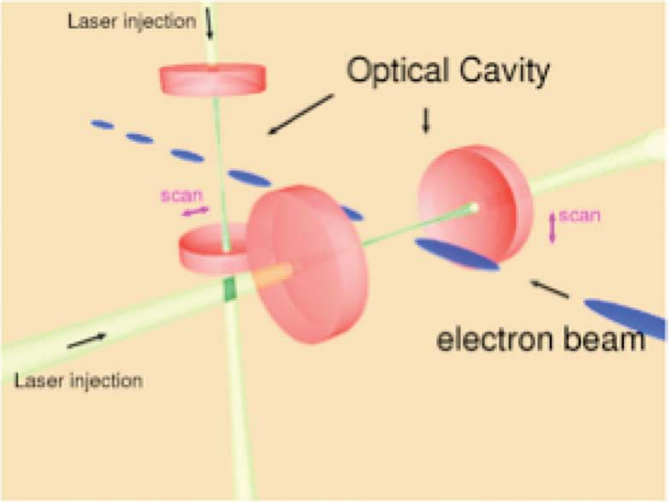
- different fringe pitch, different laser wavelength



Laserwire with an external optical cavity

- Requirements for laser target (laserwire)
  - Intensity
  - small width (w0)
- Optical cavity
  - Power build-up
  - Accurately measurable/stable waist
  -
- CW cavity
  - no need to find the right timing
  - bunch separation by signal detection timing
- Pulse cavity
  - efficient collision
  - bunch length

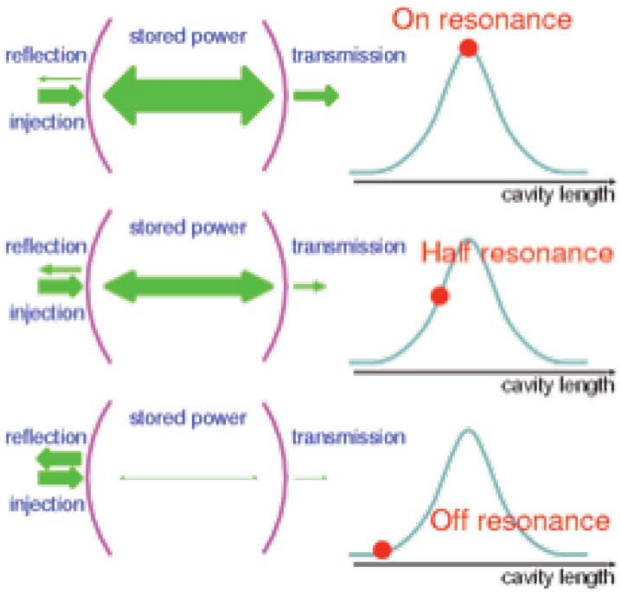


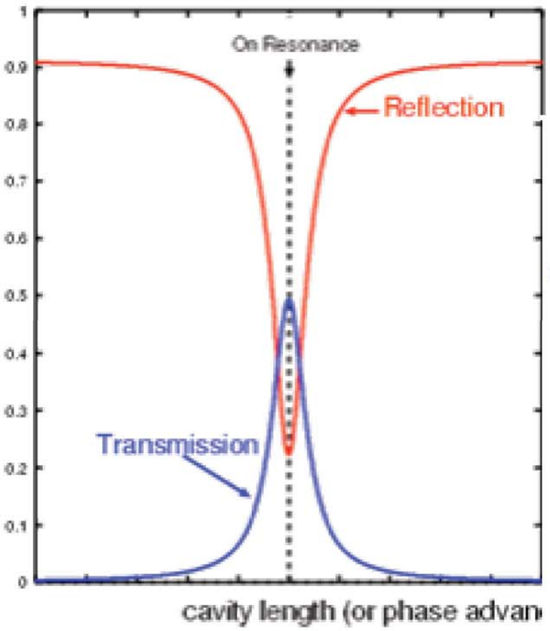


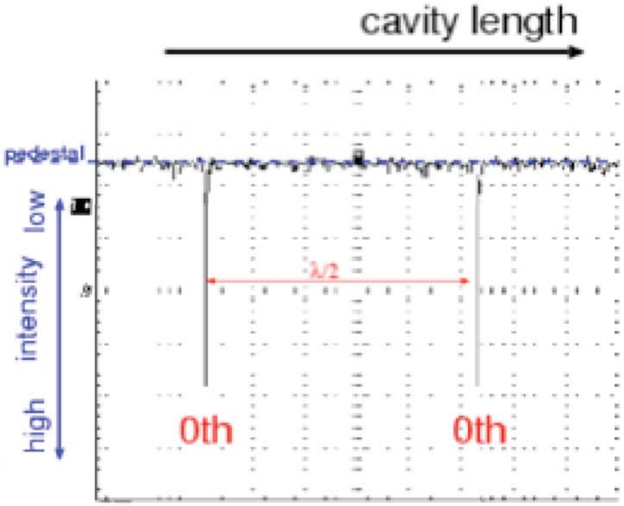
Yosuke Honda (Kyoto University / KEK)

Principles of an optical cavity (power build-up)

- Laser power builds-up if the resonance conditions are satisfied.
- Higher gain, higher reflectance, narrower resonance width.





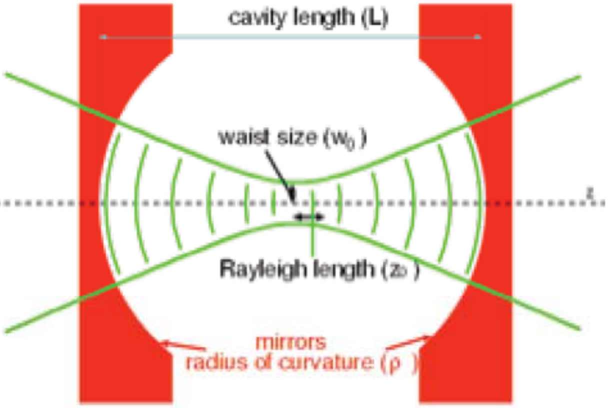


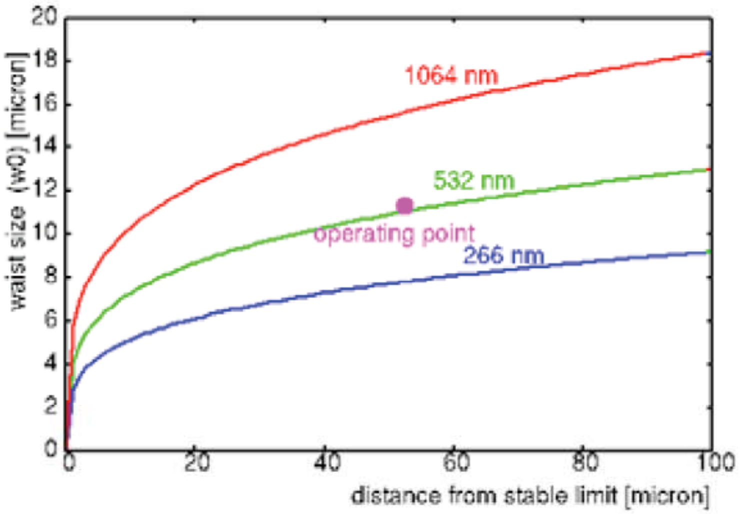
Principles of an optical cavity (waist size)

- Shape of the leaser beam is defined by the cavity, boundary condition given by the mirror. It is stable and accurately measurable.

$$w_0 = 2\sigma$$

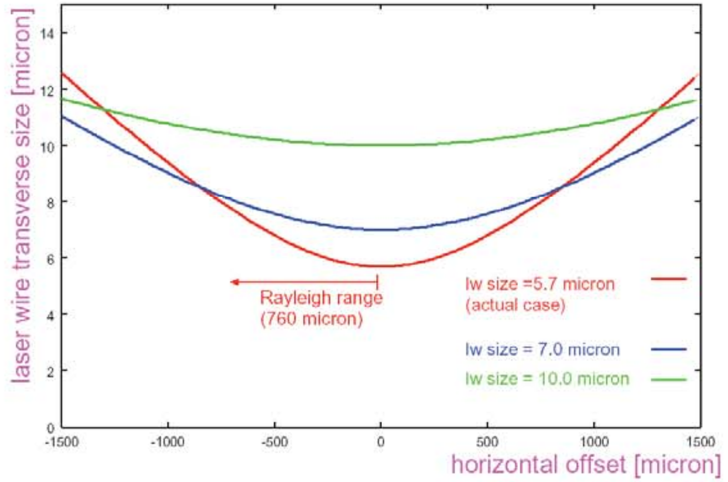
$$w_0^2 = \frac{\lambda}{\pi}\,\frac{\sqrt{L\,(2\rho - L)}}{2}$$





$$E_{mn} = A\frac{w_0}{w(z)}\exp\left(-\frac{x^2+y^2}{w^2(z)}\right)H_m\left(-\frac{\sqrt{2}\,x}{w_0}\right)H_n\left(-\frac{\sqrt{2}\,y}{w_0}\right)$$
$$\times\ \exp\left(-ik\frac{x^2+y^2}{2R(z)}\right)\exp(-i\Phi(z))\exp(i\omega t - ikz)$$

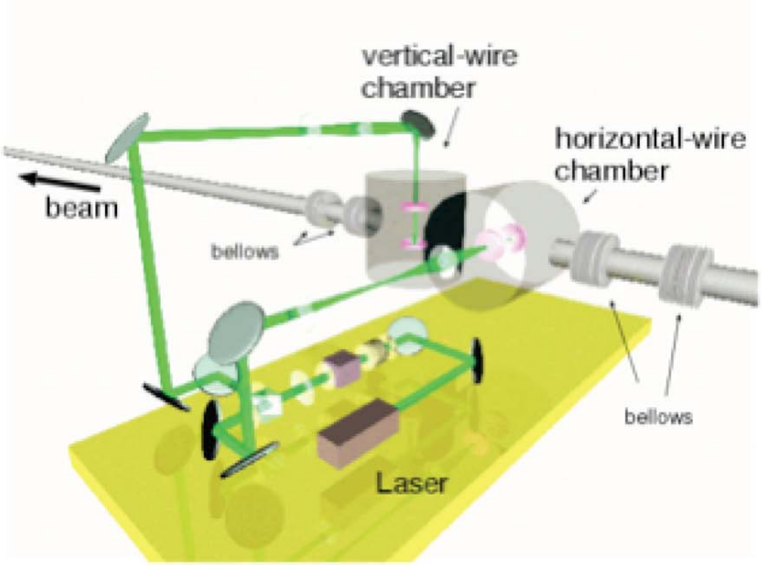
$$w(z) = w_0\sqrt{1+(z/z_0)^2}$$
$$R(z) = z\,(1+(z_0/z)^2)$$
$$\Phi(z) = (m+n+1)\arctan(z/z_0)$$
$$z_0 = \pi w_0/\lambda$$

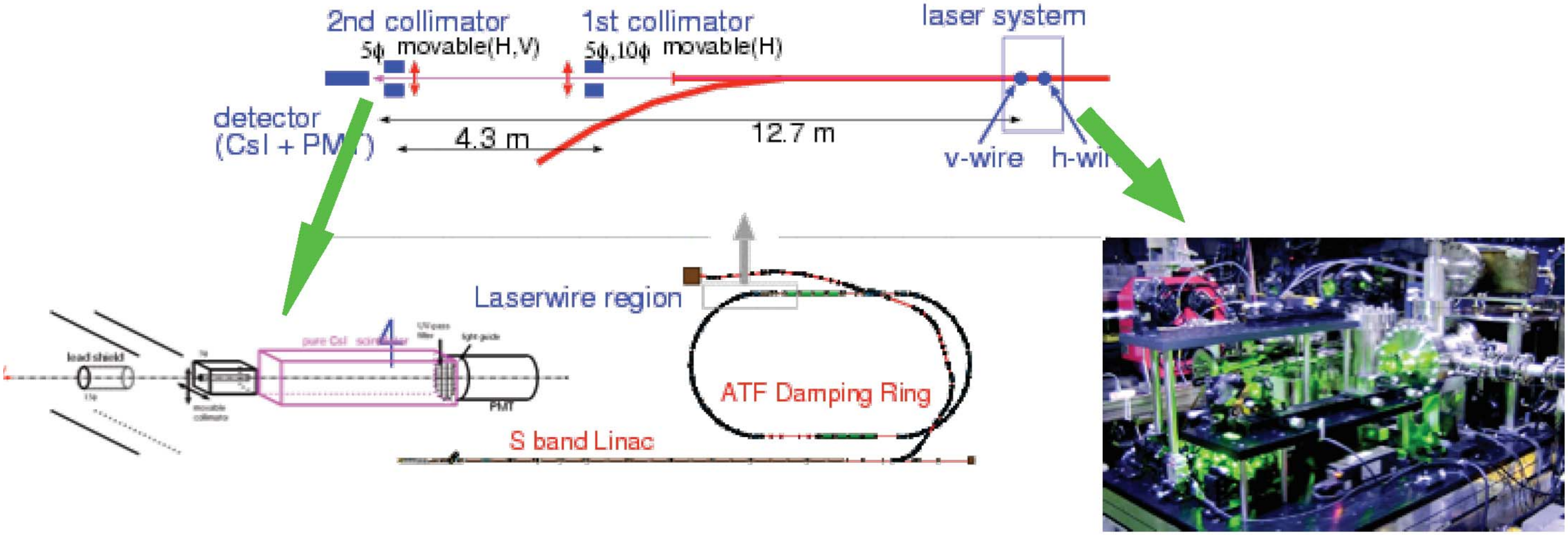


–Yosuke Honda (Kyoto University / KEK)

Setup

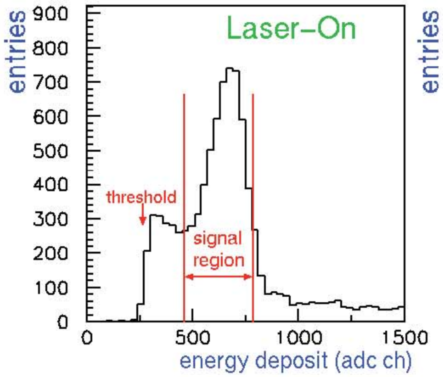
- ATF Damping ring
  - 5 micron (Y), 100 micron (X), typical beam size.
  - horizontal and vertical cavity
  - scan by mover table.
- detection
  - CsI scintillator, counting.
  - Compton edge is 28 MeV.

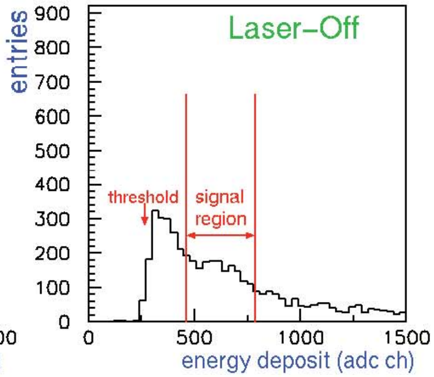


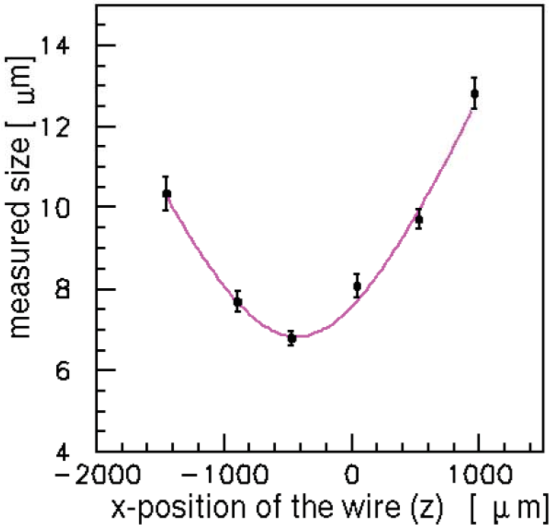


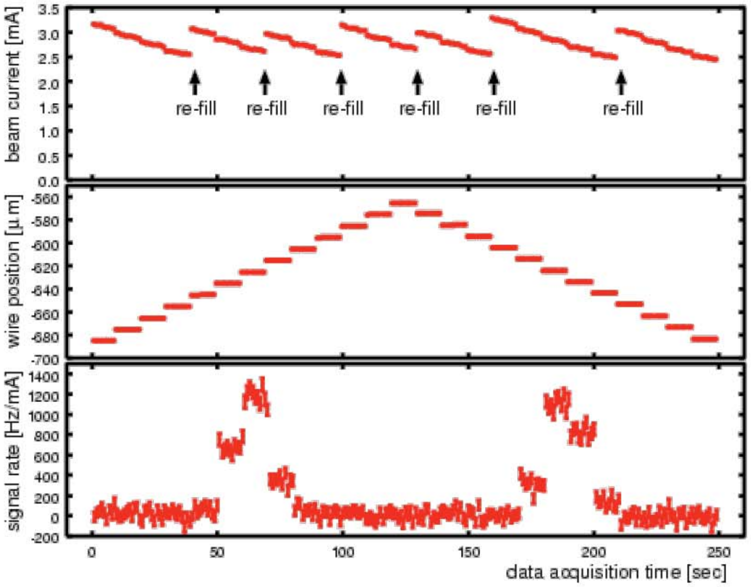
Example of the measurement

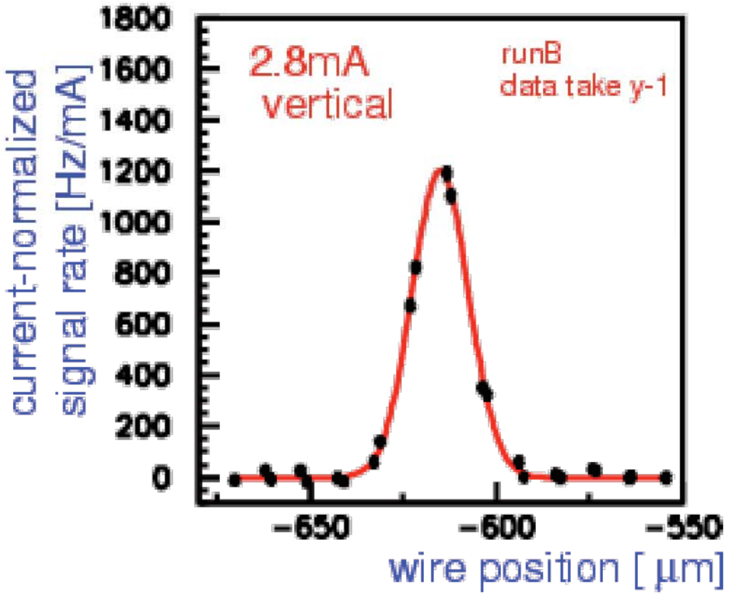
- It takes 6 min. to scan.
- Subtracting the contribution of laser's size from the measured size (in quadrature), the beam size is obtained.
    - 7.0 um (measured) - 5.6 um (laser) = 4.2 um









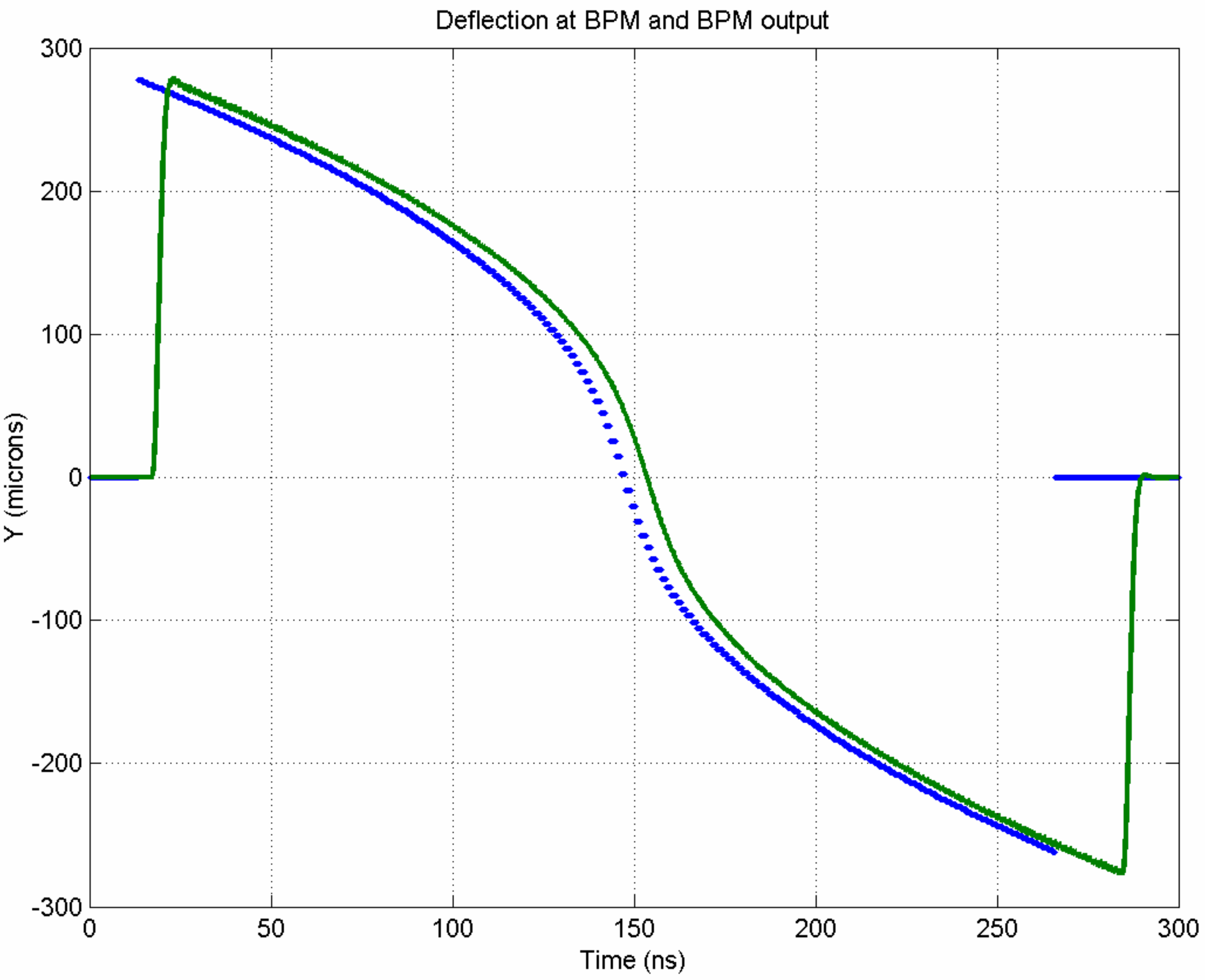


Beam size measurements at IP

- the finest (only) probe suitable at the IP is the other beam
  - use the beam-beam deflection
- 250 x 3 x 200000 nm
  - factor 10 below limiting performance of fringe monitor
  - aspect ratio of a thin 1mm strip of very thin 15 um foil, 1 m long

- No independent monitor is foreseen…

Beam-Beam Scan



Beam bunches at IP: blue points

BPM analog response: green line

Bunch Length Monitors

- Time scales are so short:
  - ILC ~ 200um or 600 femtoseconds – ($c/2\pi\lambda$ ~ 0.24THz)
  - FEL ~ 10 um or 30 femtoseconds – (~ 5THz)
  - (too fast for most mixers)
- Use a strong RF deflection – time dependent sideways kick →
  - Kick the head of the beam one way & the tail the other
- Looks just like a normal warm RF structure – except slightly larger
  - Can also be done with cold RF
- We sense these dipole fields in the TESLA cavity – we drive them *hard* here…

Summary of bunch length monitors

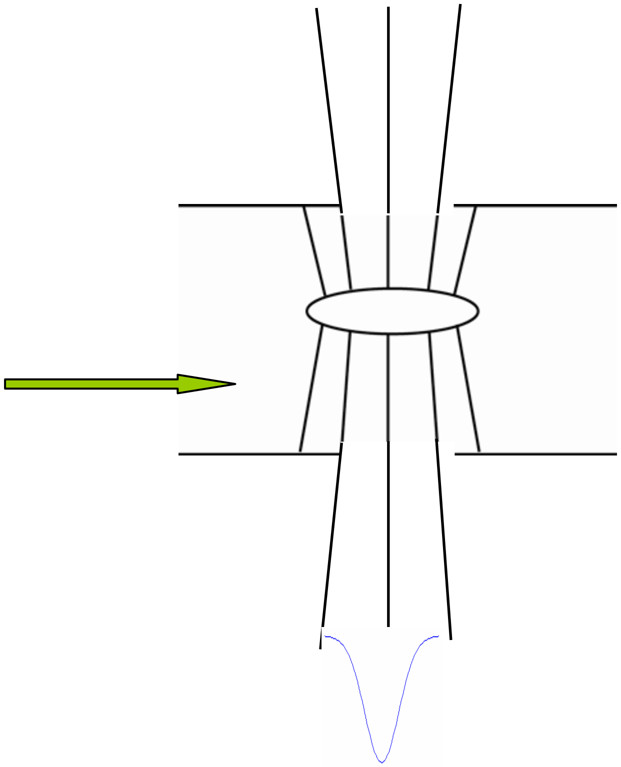
- Free electron lasers require very high peak current – this has pushed development of bunch length monitors

- deflecting structures
  - warm or cold
  - single bunch (warm) or full train (crab: cold)
  - require an imager
- infrared / mm wave detectors
  - diffraction radiation
  - coherent synchrotron radiation
  - simple ceramic gap
- electro-optic
  - use of non-linear optical materials
  - the material optical properties depend on the field of the beam; probed by a laser.

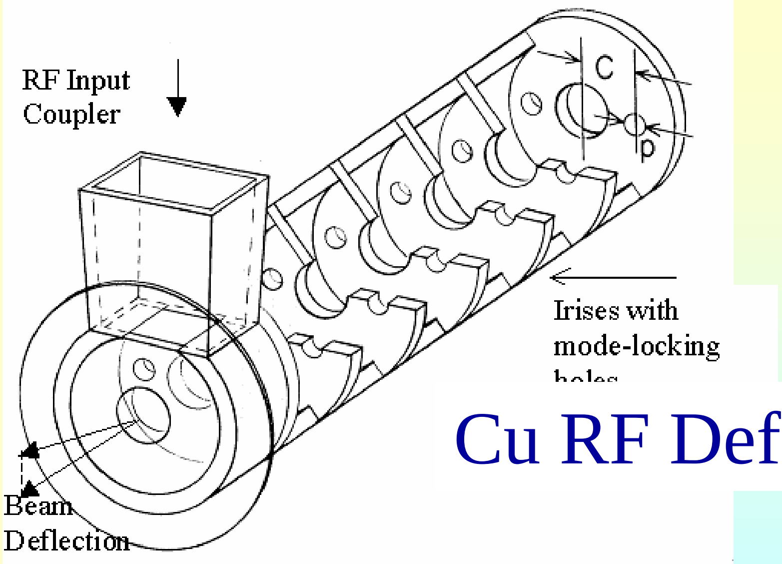
Gap monitor

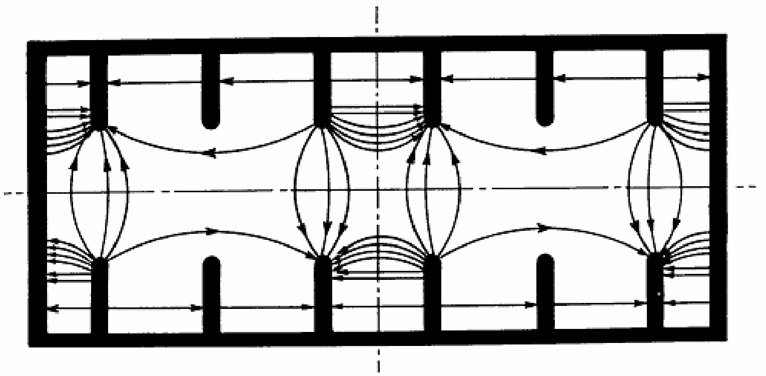
- simple ceramic gap in the beamline vacuum enclosure:

- detect the emitted field with a fast diode
  - frequencies ω~ sig_z
  - 200 um ~ 250 GHz (ILC)
- the diode has a bandwidth, several are needed to cover a reasonable range
- inexpensive, broad band, uncalibrated system

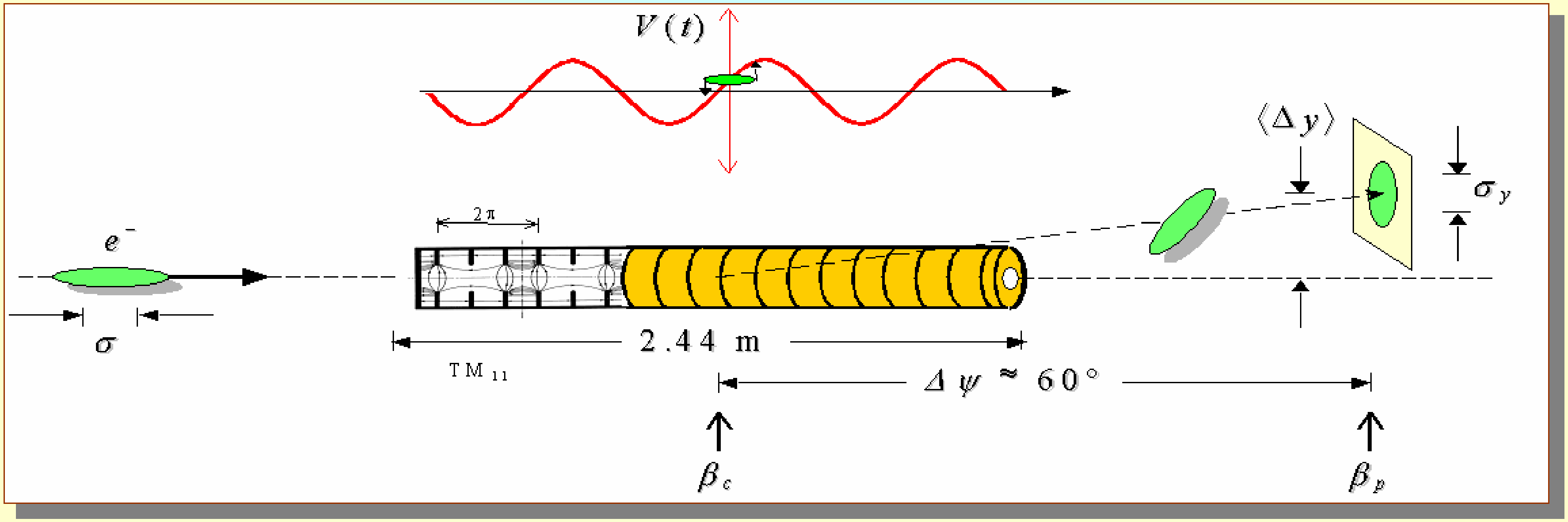


Cu RF Deflecting Structure and Profile Mon.





$$\text{bunchlenght}, \sigma_z \approx \frac{\lambda_{\text{rf}}}{2\pi} \frac{E_S}{\left|eV_0 \sin\Delta\psi \cos\varphi\right|} \sqrt{\frac{\left(\sigma_y^2 - \sigma_{y0}^2\right)}{\beta_d \beta_s}}$$



Reference 4

Deflecting RF structures (‘crab’)

$$V_0 = 1.6L\sqrt{P_0}$$

L has units m, *P* MW and *V_0* MV

$$\Delta x'(z) = \frac{eV_0}{pc}\sin(kz+\varphi) \approx \frac{eV_0}{pc}\left[\frac{2\pi}{\lambda}z\cos\varphi + \sin\varphi\right]$$

the angular centroid kick – in x or y

$$\Delta x = \sqrt{\beta_1\beta_2}\,\sin\Delta\psi\cdot\Delta\theta$$

offset at *2* based on angle at *1*

$$\sigma_x = \sqrt{\sigma_{x0}^2 + \sigma_z^2\beta_d\beta_s\left(\frac{2\pi eV_0}{\lambda\gamma m_e}\sin\Delta\psi\cos\varphi\right)^2}$$

beam size on imager ‘s’. Two terms: nominal and ‘deflected’

$$|eV_0| \ge \frac{\lambda}{\pi\sigma_z}\frac{m_e}{|\sin\Delta\psi\cos\varphi|}\sqrt{\gamma\frac{\varepsilon_N}{\beta_d}}$$

Needed kick for the ‘deflected’ term to be ~ larger → resolution

Note: m_e = 0.511 MeV

Crab structures:

$V_0 = transverse\_voltage$

$L = length$

$P_0 = peak\_input\_power$

$pc = \gamma m_e$

$$k = \frac{2\pi}{\lambda}$$

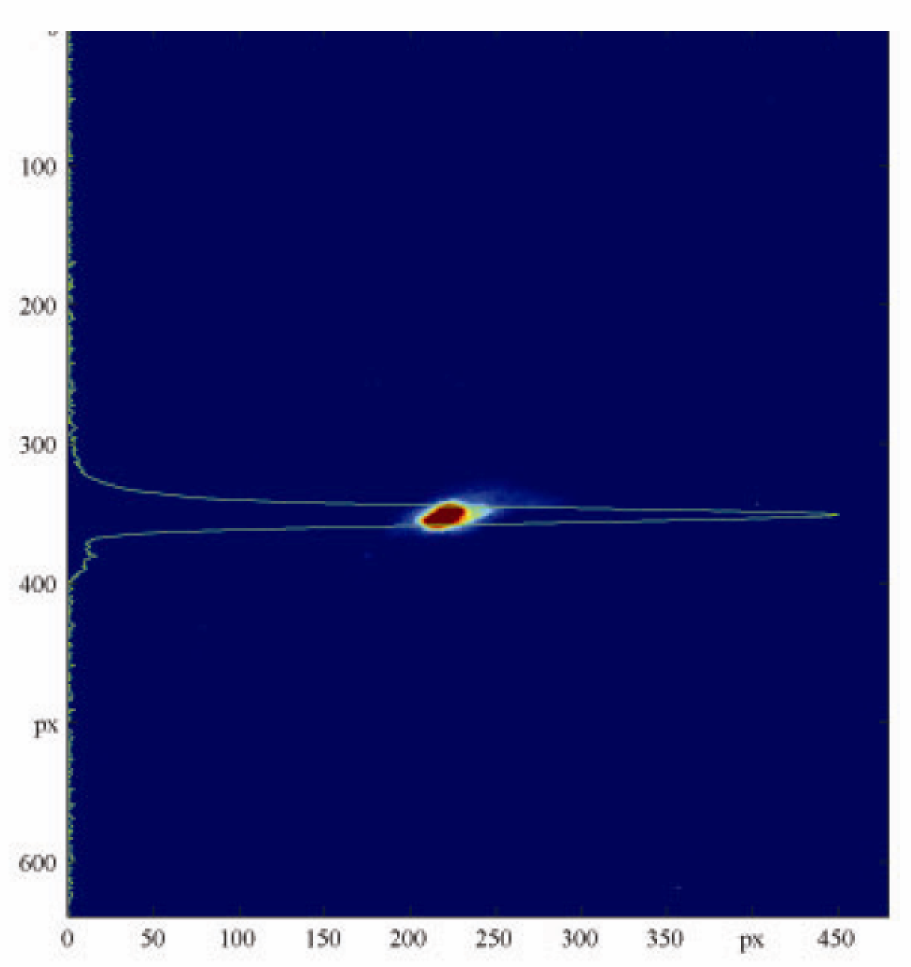
$\lambda = wavelength\_deflector\_RF$

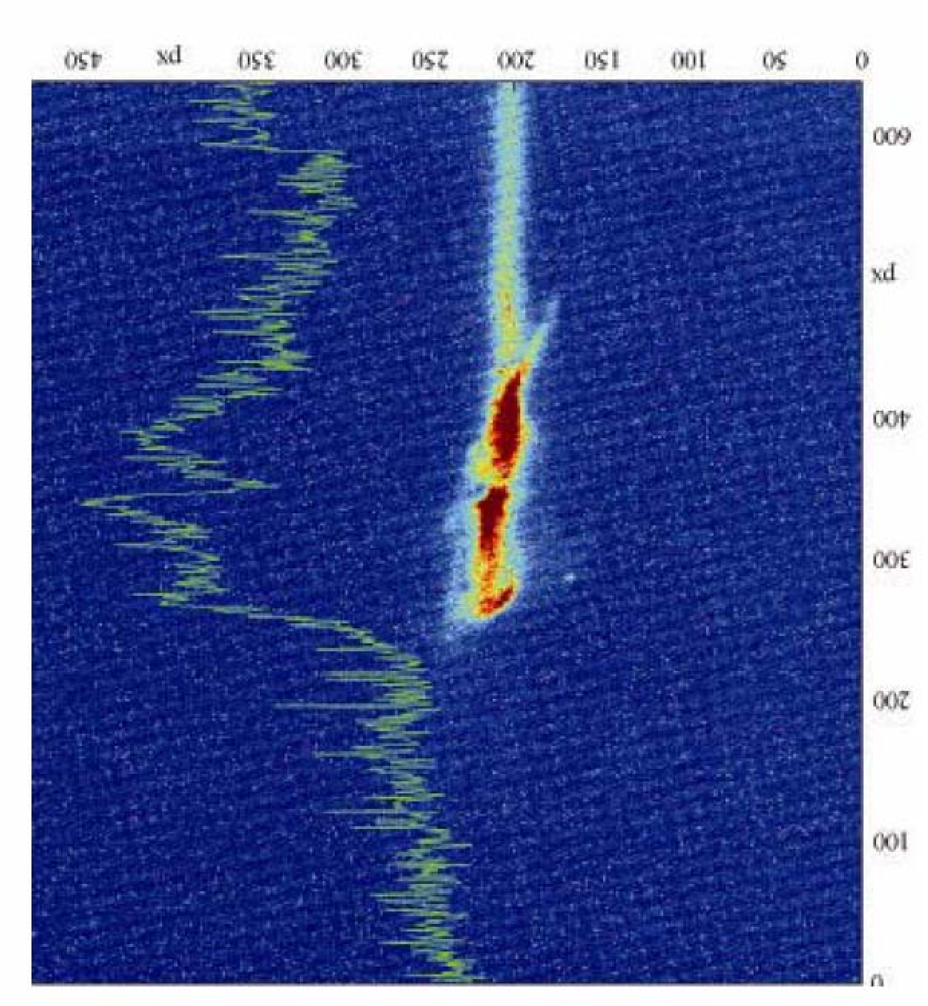
$\varphi = RF\_phase\_(0\_at\_zero\_cross)$

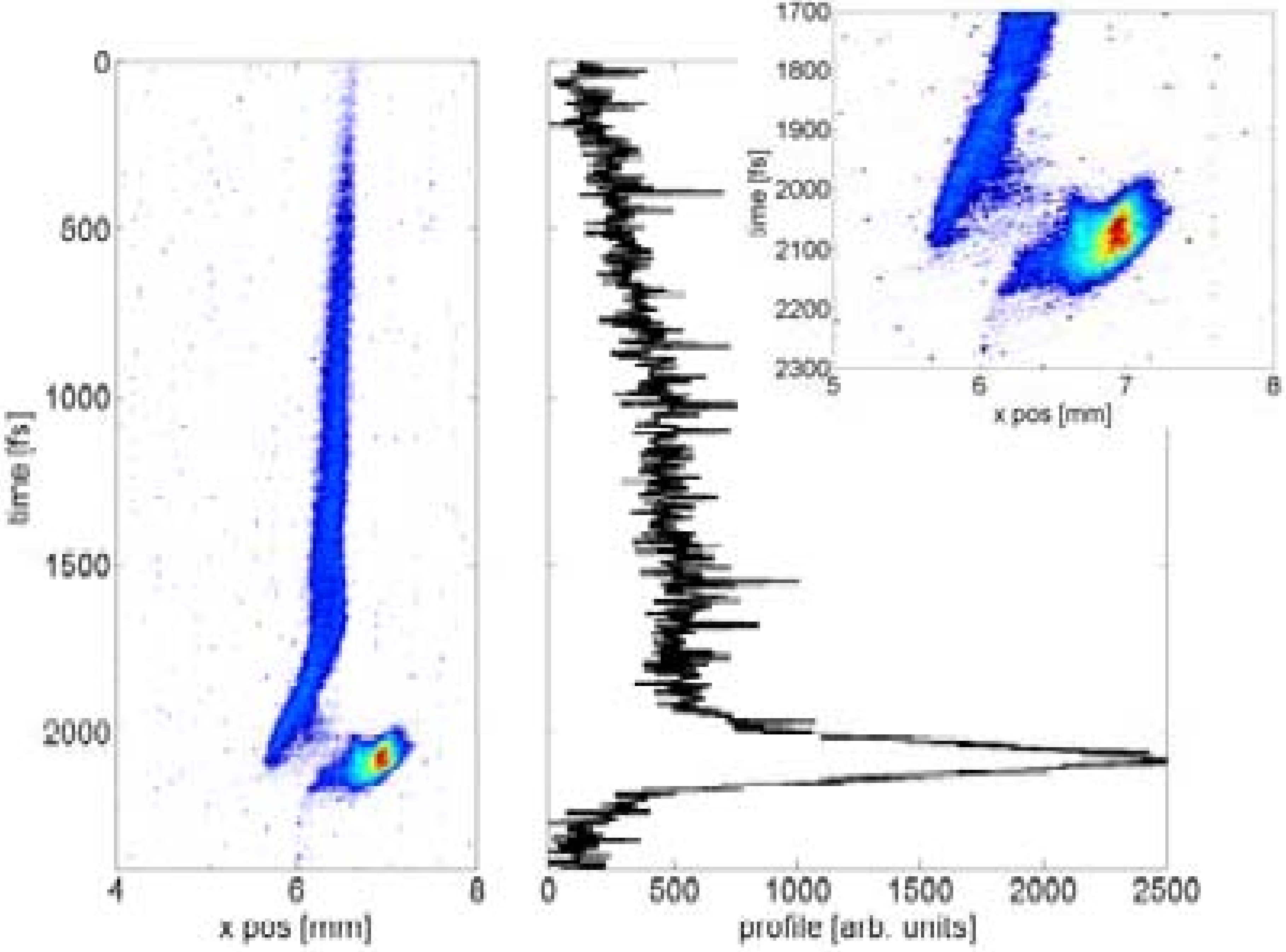
$\Delta\psi = machine\_optics\_phase\_advance$

$\beta = machine\_optics$

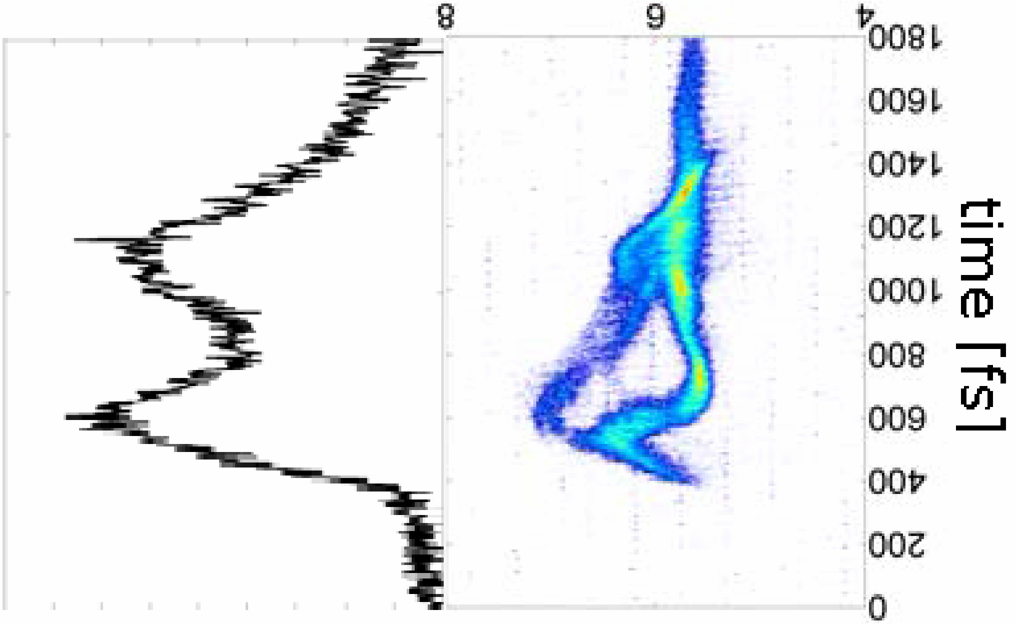
Deflector on/off

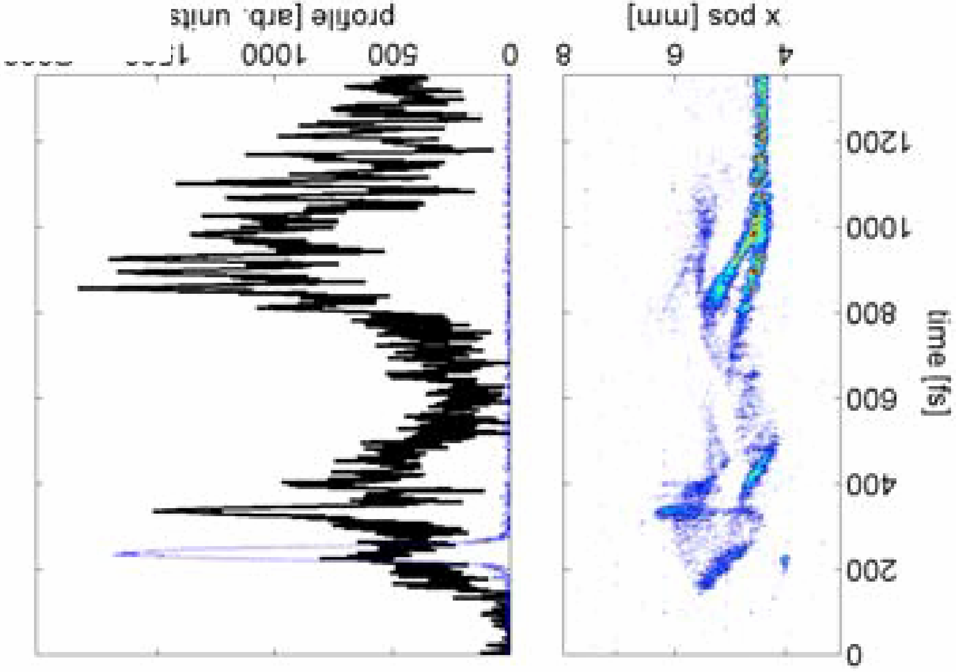




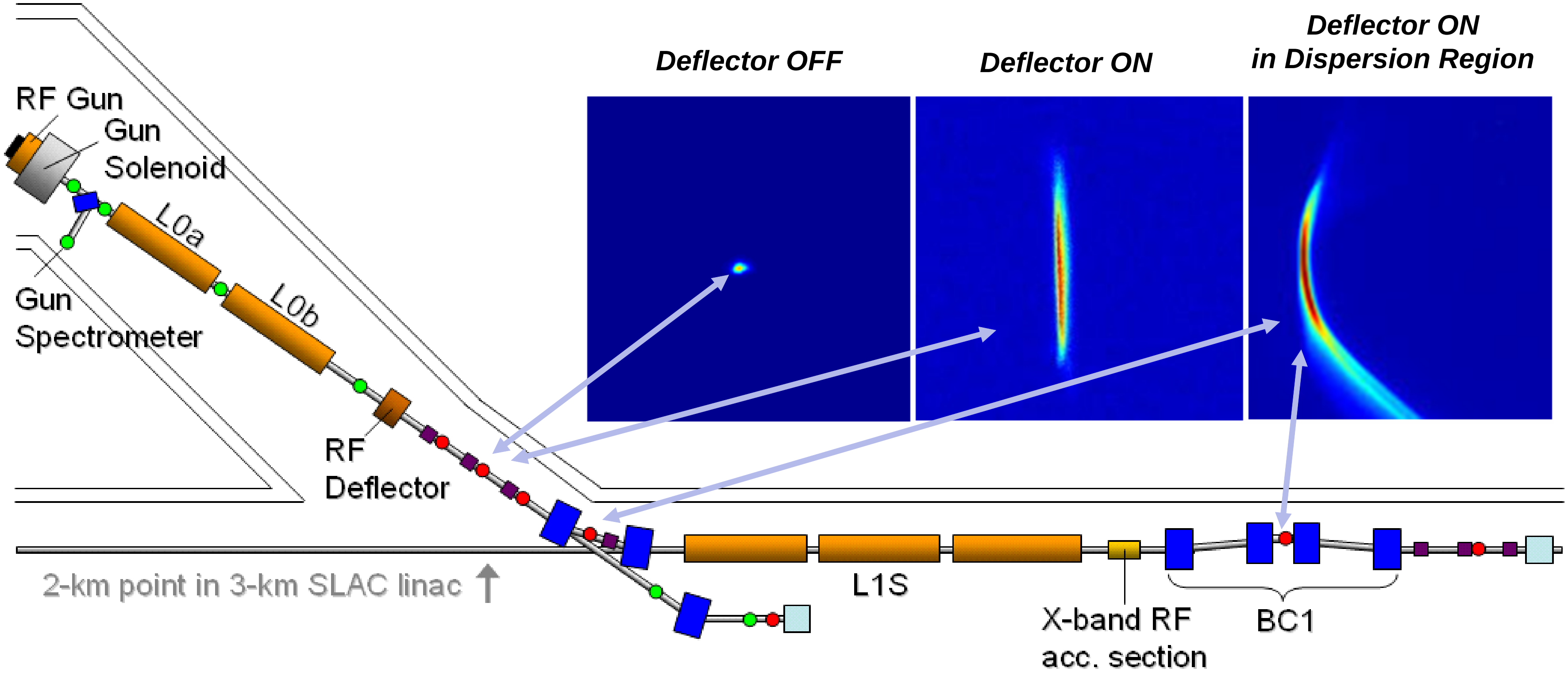

0
500
1000
1500
2000
time [fs]
4
6
8
x pos [mm]
0
500
1000
1500
2000
2500
profile [arb. units]
1700
1800
1900
2000
2100
2200
2300
time [fs]
5
6
7
8
x pos [mm]

Deflector Images from ‘TTF – FLASH’



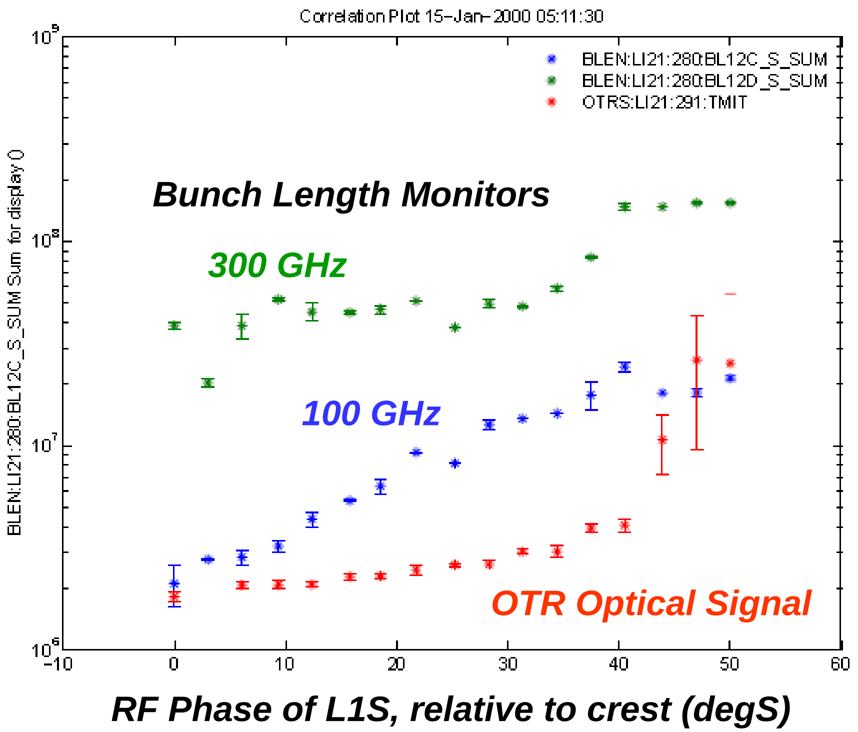


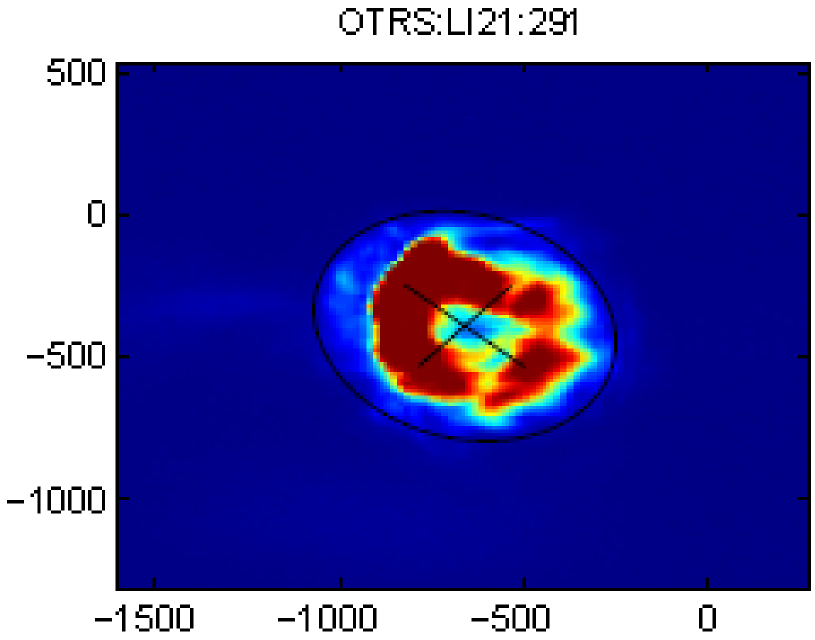
Use of RF Deflector – SLAC 'LCLS'



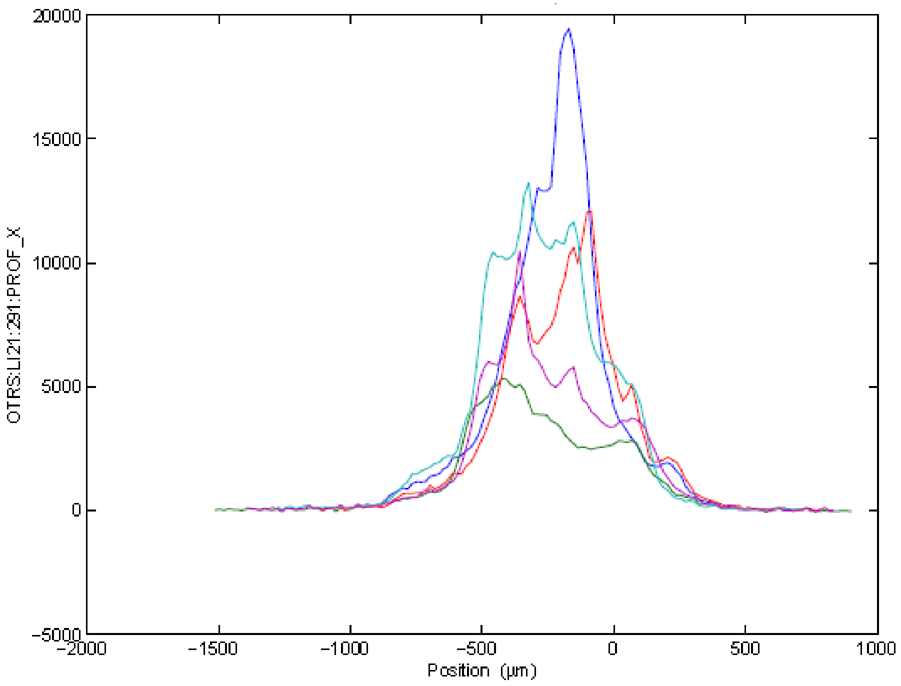
Coherent radiation

- Radiated power in small – wave band increases with short bunches
- Coherent radiation makes ‘useless’ the OTR monitor
  - Basically a mirror in the vacuum chamber



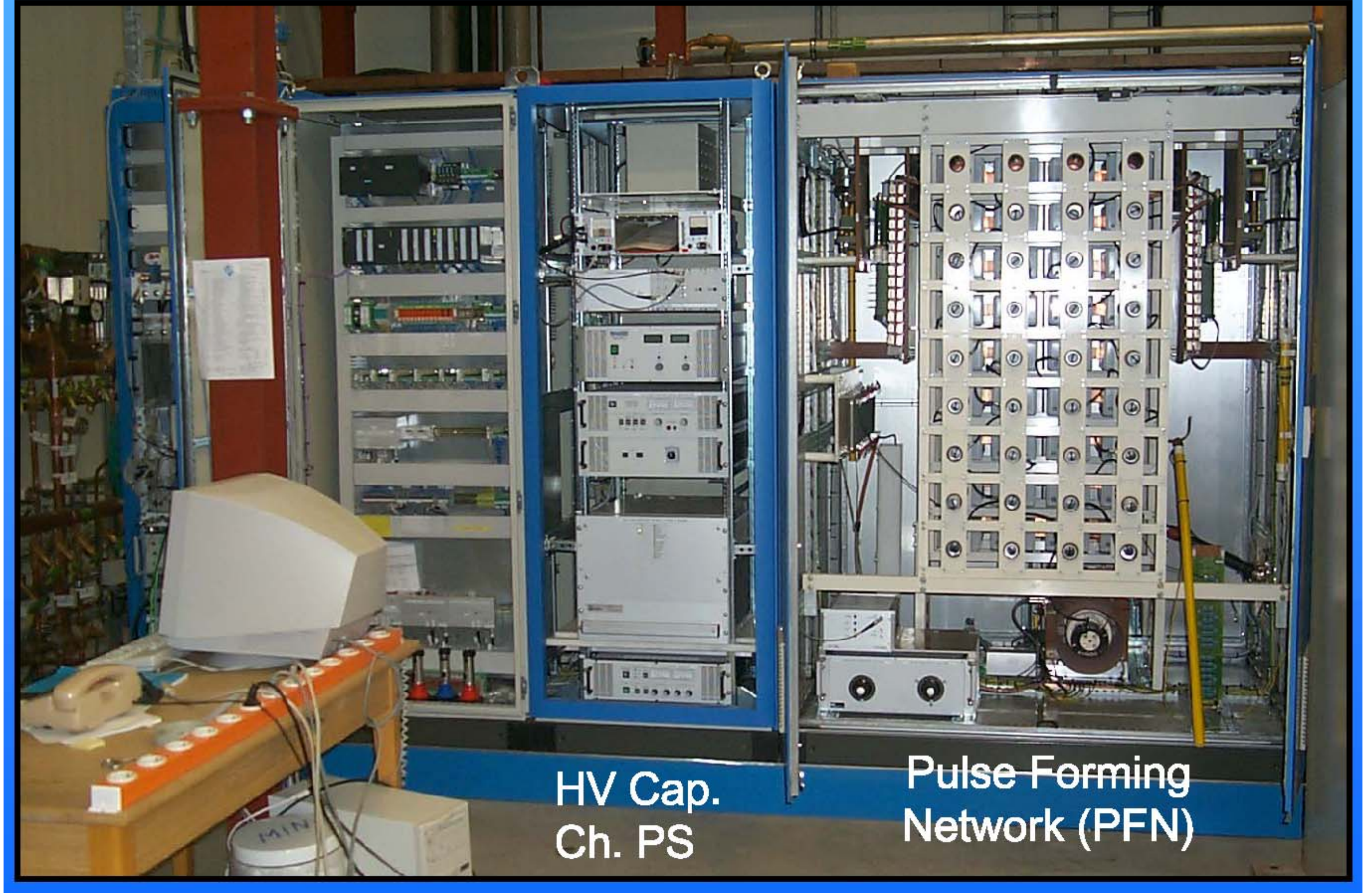


Ross -
hool o



The Modulator and its components:

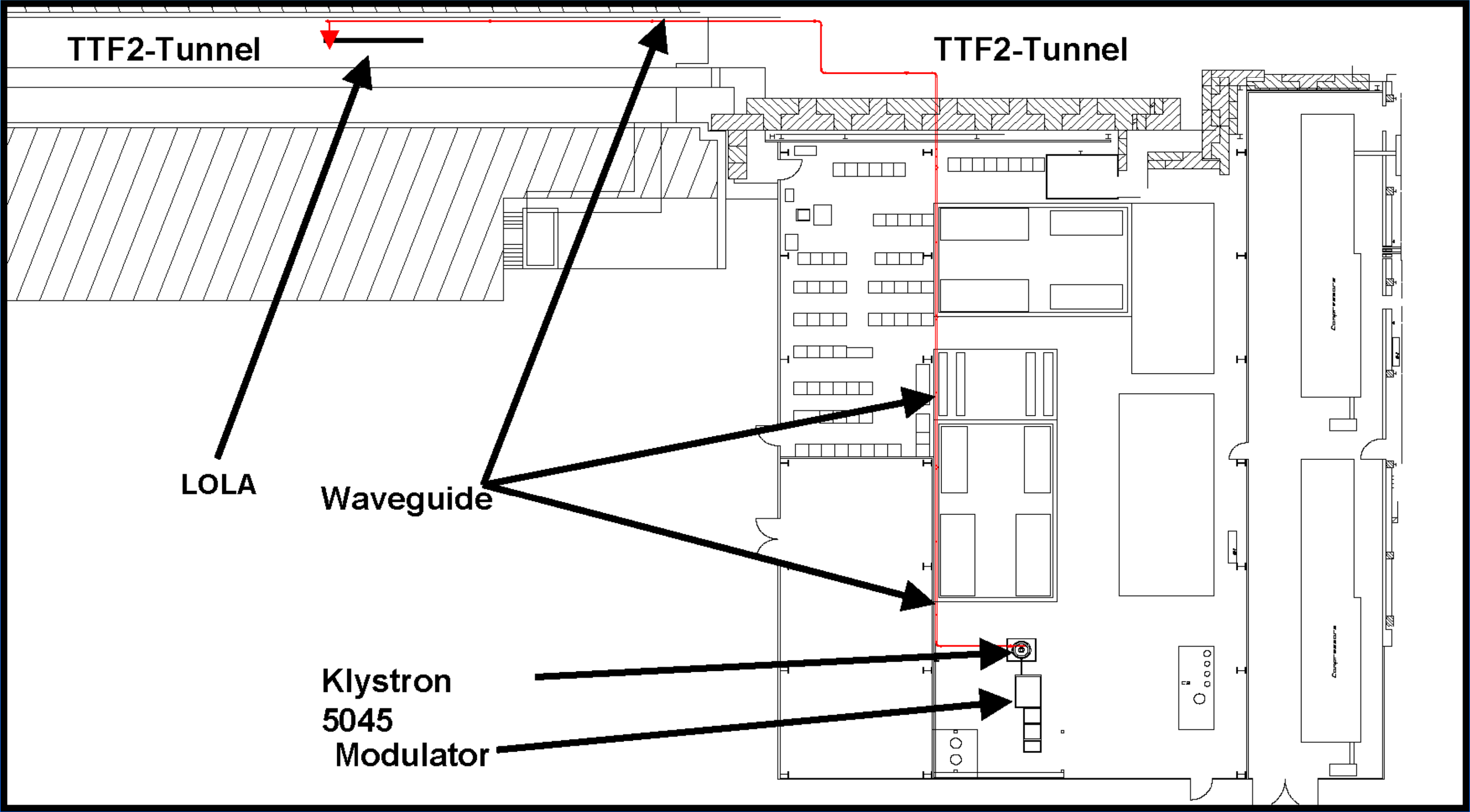
- The 150 MW modulator with a pulse width of 5µs and a repetition frequency of 10 Hz was ordered at PPT by DESY.
- It is a line-type pulser with a 50 kV capacitor charging power supply and a SPS control system incl. Ethernet interface.

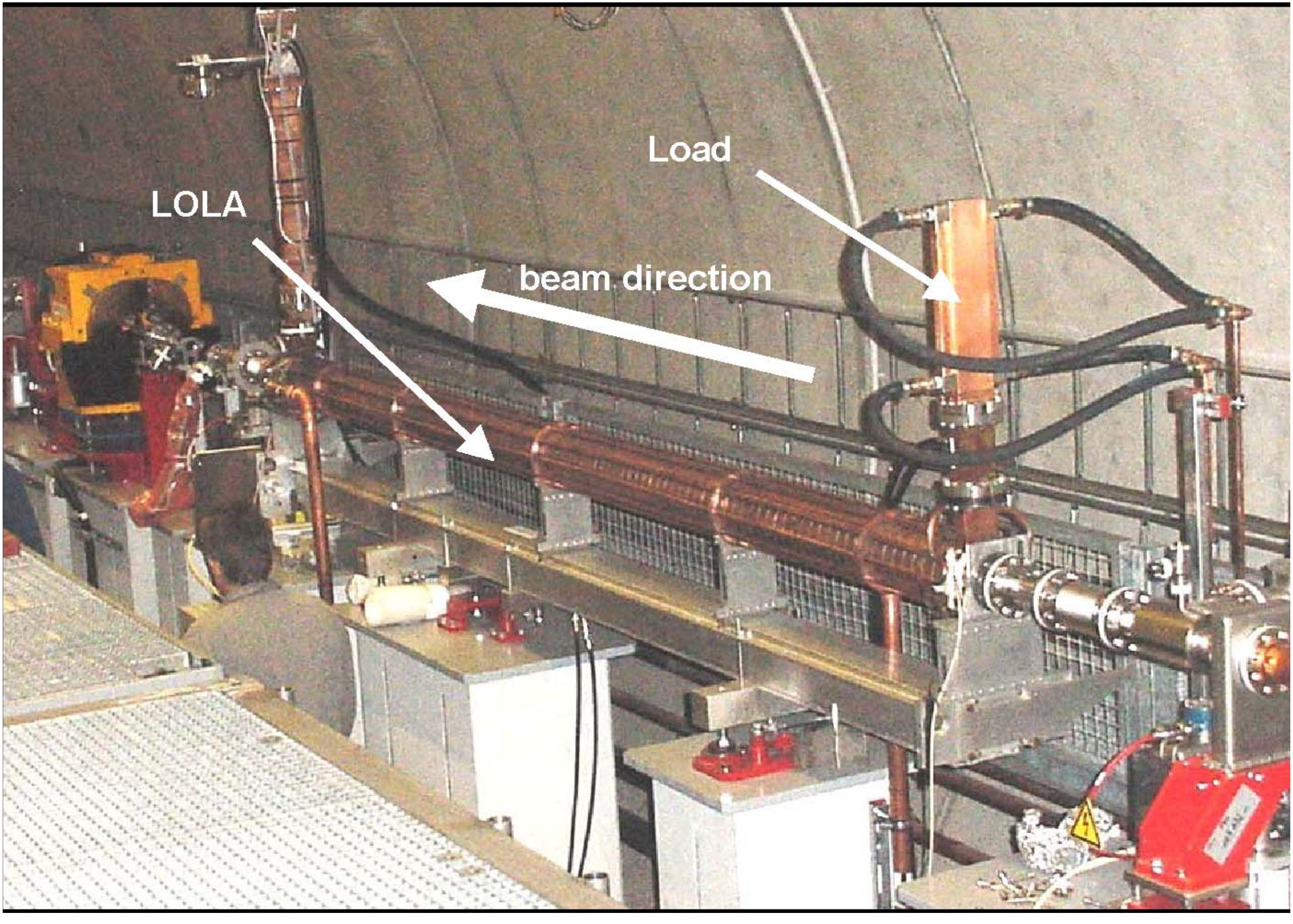


5. Waveguide and LOLA Commissioning

The Waveguide:

The waveguide length between klystron and LOLA is 75 m. The theoretical attenuation is 1.6 dB, measured was 2.6 dB. The maximal power on the waveguide is 45 MW and at the LOLA input 25 MW. The waveguide material was contributed by SLAC. Brazing and machining was done at DESY. As the phase shift is 2.8°/K the waveguide is heater stabilized at 35°C.




Load
LOLA
beam direction

Reference 5

Feedback

- First order: steering, timing, energy
  - ‘set value’ is best
  - ‘cruise control’, as in a car
- First order: low latency within the train
- Second order: luminosity, energy spread, emittance, background?
  - optimum or max/min is best
  - parabolic response
  - feedback on the ‘derivative’ – *excitation required*
- Feedforward
- Ring feedback systems

Purpose of feedback

- Thermal, mechanical, beam dynamics, human, electrical, and geophysical effects drive instabilities that can be cured with feedback
  - such a broad range results in a wide variety of systems
  - all have same low level block diagram
- Control theory develops systems that account for complex transfer functions
  - ‘State Vector’ notation is useful for design and implementation
  - denotes the abstract ‘state’, the measurements, their relationship (hopefully through fixed matrices), evolution, and the impact of our control

Purpose of Feedback (2)

- a wide range of feedbacks from steering loops in a 5 Hz linac to Fox's longitudinal feedback in PEP-II that actually makes an unstable beam stable.
- lets one maintain a parameter (e.g. energy) more easily than providing good enough control of parameters that effect it (e.g. temperatures, phases etc.);
- lets one tune while masking downstream effects (e.g. steer RTL without orbit in linac changing; can typically only control disturbances a factor of 30 or more below the sampling frequency;
- Frees up operators from turning knobs.
- Problems caused if input measurements are bad (can make an otherwise nondisruptive BPM failure cause significant downtime)

Reference 6

State Vector Notation

$$x_{i+1} = Ax_i + Bu_i$$

the next state (x) follows (A) from this one and the changes we make (u)

$$u_i = G_{ctl} x_i$$

The changes we make are derived from state through the gain matrix (G)

$$x_{i+1} = Ax_i + Bu_i + d_i$$

In reality, there are instabilities (d)

$$y_i = Cx_i + e_i$$

we have a set of measurements (y), which depend on the state (C) and have noise (e)

$$x_i = Ax_{i-1} + G_{est}(Y_i - CAx_{i-1})$$

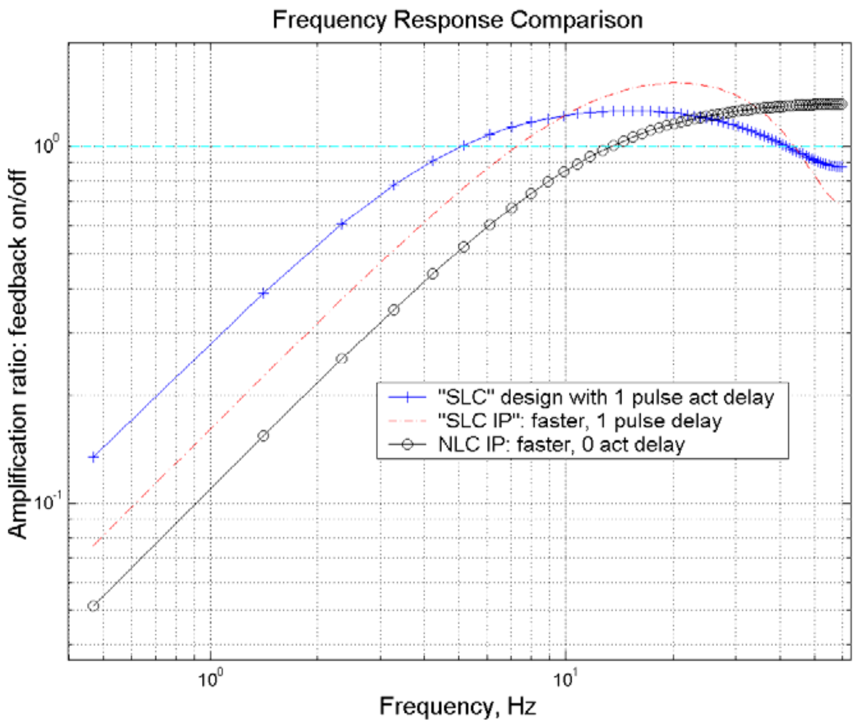
‘Free-evolve the state, predict the measurement from the evolved state, subtract it from the actual measurement to get the residual, multiply by estimator gain vector *G_est* , and add’.

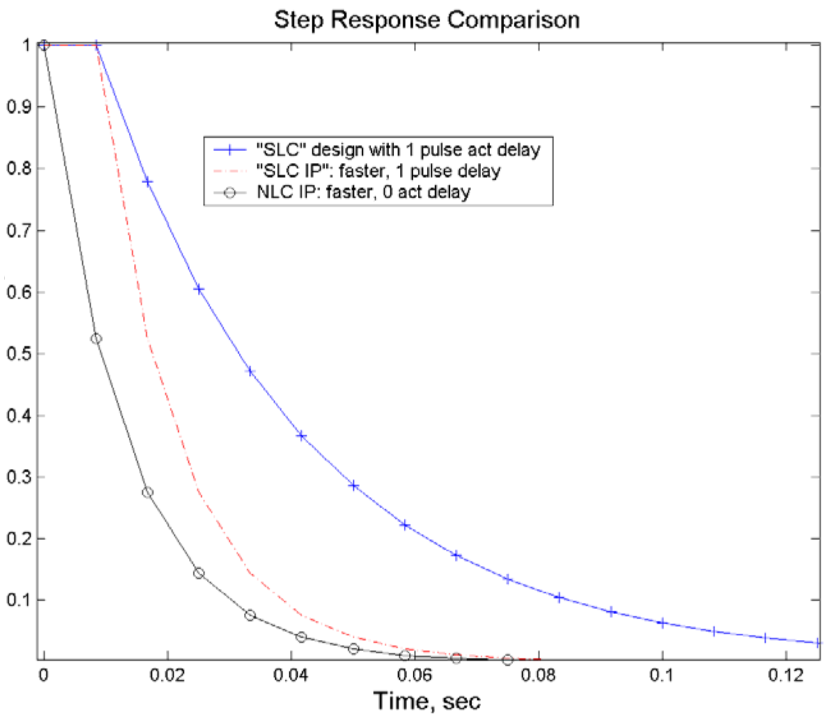
Example feedback loops

- Simple:
  - energy and steering
  - collisions
- Complex:
  - LLRF phase and amplitude control (esp in bunch compressor)
  - Damping ring coupled bunch instability
  - inter-linac timing

Feedback timescales: NLC vs SLC feedback design response:

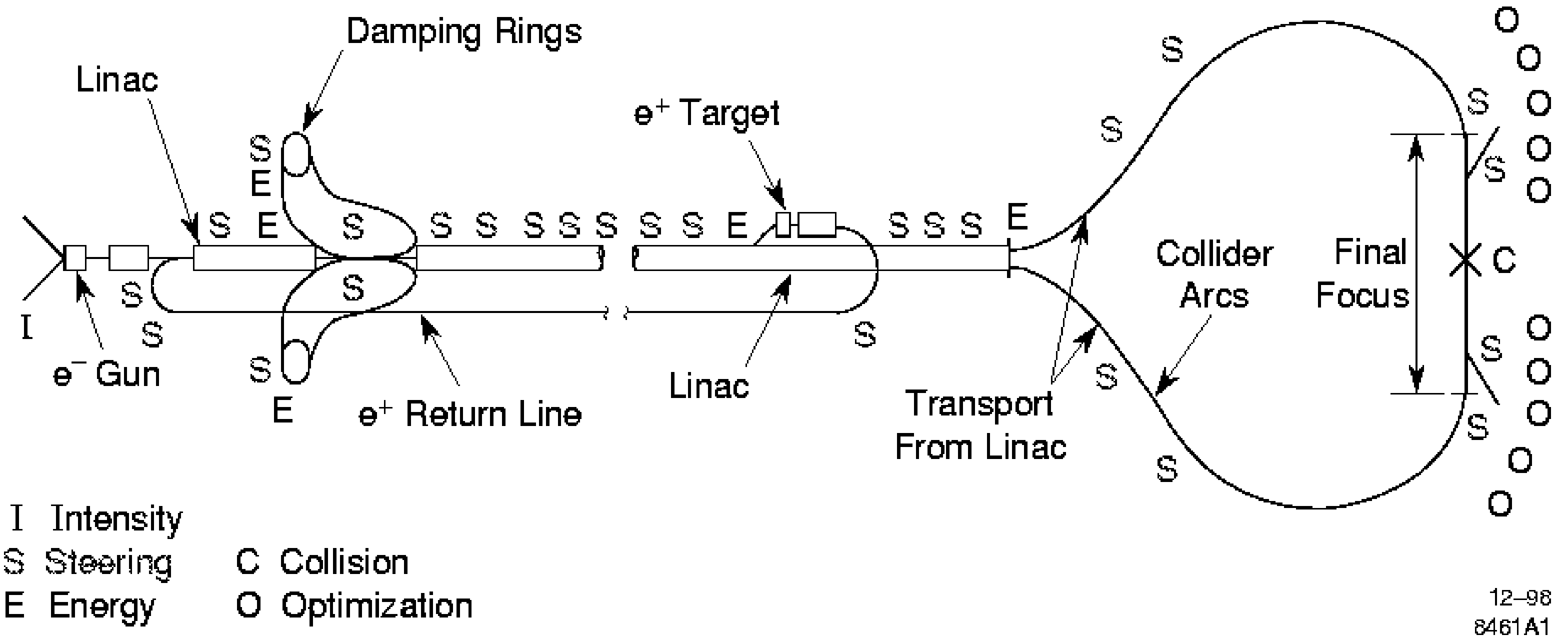
(It helps to assume a faster control system: low-latency BPMs, fast IP kickers/correctors)





Feedback loops used at SLC

- Five different kinds
- Dominated by steering
- reflects observed level of instability



ILC Feedbacks – damping ring

- **Damping Ring: Injection trajectory control**
  - Purpose: maintain injection efficiency close to 100%
  - Monitors: injection orbit via bpms
  - Actuators: setpoints for injection kicker and septum.
  - Correction plane: horizontal
  - Correction sampling rate: 5Hz
- **Damping Ring: Dynamic orbit control**
  - Purpose: compensate for drift and low frequency disturbances to keep beam through center of the multipoles
  - Monitors: closed orbit via NN bpms.
  - Actuators: MM correctors.
  - Correction plane: horizontal and vertical
  - Correction sampling rate: 10-20KHz.
- **Damping Ring: Bunch-by-bunch transverse feedback**
  - Purpose: reduce coupled-bunch instabilities.
  - Monitors: single wide-bandwidth bpm to provide bunch-by-bunch signals.
  - Actuators: fast deflecting cavity or striplines.
  - Correction plane: horizontal and vertical
  - Correction rate: full bunch rate (500/650MHz)
- **Damping Ring: Extraction orbit control**
  - Purpose: preserve emittance through extraction septum
  - Monitors: emittance of extracted beam from RTML
  - Actuators: correctors in damping ring.
  - Correction plane: horizontal and vertical
  - Correction sampling rate: 5Hz

RTML (Bunch compressor) Feedbacks

- **Ring to Main Linac: Pre-Turnaround emittance correction.**
  - Purpose: reduce emittance growth
  - Monitors: emittance measurement.
  - Actuators: dipole correctors and skew quads
  - Correction sampling rate: 5Hz for dipole correctors, <1Hz for skew quads
- **Ring to Main Linac: Turnaround trajectory feed-forward**
  - Purpose: correct for extraction kicker jitter.
  - Monitors: beam trajectory measured upstream via bpms.
  - Actuators: 2 fast correctors per plane.
  - Correction plane: horizontal and vertical
  - Correction sampling rate: bunch spacing (~3MHz)
- **Ring to Main Linac: Post-Turnaround emittance correction**
  - Purpose: minimize emittance growth.
  - Monitors: emittance measurement.
  - Actuators: 4 skew quads
  - Correction sampling rate: 5Hz for dipole correctors, <1Hz for skew quads
- **Ring to Main Linac: Beam energy at bunch compressor (two stages)**
  - Purpose: control the final beam energy
  - Monitors: bpms in high-dispersion sections.
  - Actuators: klystron phase shifters
  - **Correction sampling rate: 5Hz**
- **Ring to Main Linac: Linac injection phase**
  - **Purpose: control the inter-bunch time difference at the IP**
  - **Monitors: timing difference monitor near IP**
  - **Actuators: klystron phase shifters**
  - **Correction sampling rate: within the train**

Main Linac Feedbacks

- Main Linac: Trajectory Feedback (several cascaded loops)
  - Purpose: compensate for drift and low frequency disturbances to keep beam through center of multipoles and RF cavities.
  - Monitors: multiple bpms in each large section.
  - Actuators: nominally 4 horizontal and 4 vertical correctors per section.
  - Correction plane: horizontal and vertical.
  - Correction sampling rate: 5Hz.
- Main Linac: Dispersion measurement and control
  - Purpose: provide means to measure dispersion; provide means to apply local dispersion correction.
  - Monitors: dispersion measurement, laser wire.
  - Actuators: use local RF amplitude control to generate local dispersion ‘bumps’ (Dispersion free steering).
  - Correction sampling rate: ??
- Main Linac: Beam energy (several cascaded sections)
  - Purpose: control the final beam energy
  - Monitors: bpms in high-dispersion sections.
  - Actuators: klystron phase shifters
  - Correction sampling rate: 5Hz

Beam Delivery Feedbacks:

Beam Delivery System: Trajectory feedback from pulse to pulse

- Purpose: compensate for drift and low frequency disturbances to keep beams directed towards the interaction point.
- Monitors: nominally 9 bpms per plane.
- Actuators: nominally 9 correctors per plane.
- Correction plane: horizontal and vertical.
- Correction sampling rate: 5Hz

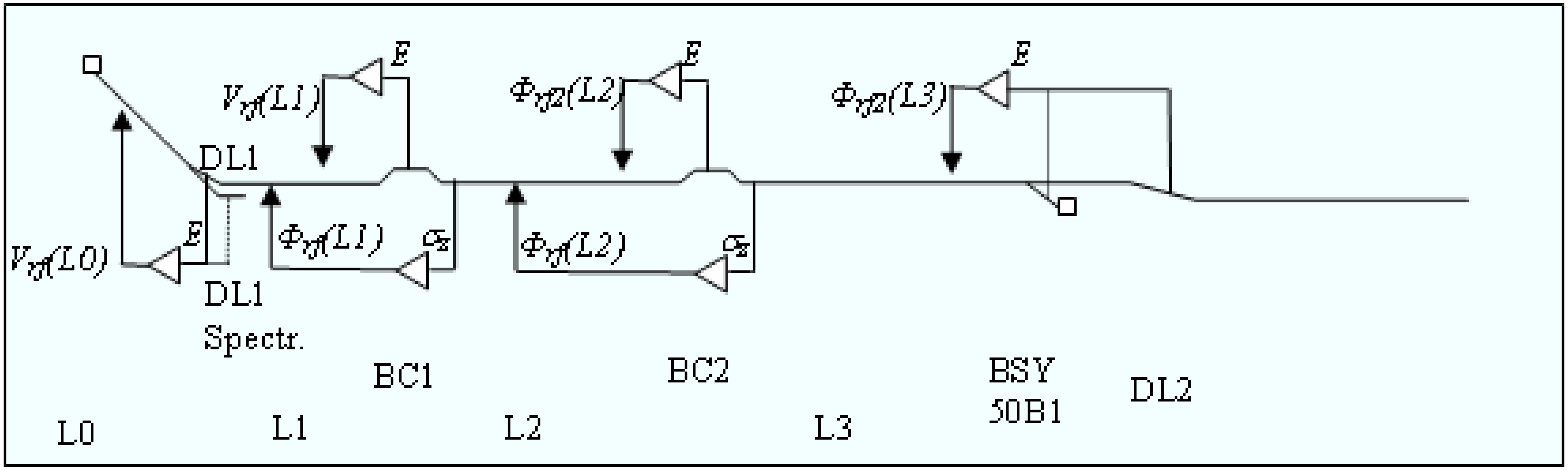
Interaction Point: Trajectory feedback from pulse to pulse

- Purpose: maximize average cross-section of colliding beams
- Monitors: post-IP measurement of beam trajectory, beam charge
- Actuators: nominally one corrector per plane.
- Correction plane: horizontal and vertical
- Correction sampling rate: 5Hz

Interaction Point: Trajectory feedback within bunch-train

- Purpose: maximize bunch-to-bunch cross-section of colliding beams.
- Monitors: bunch-by-bunch bpms.
- Actuators: 2 fast kickers per plane.
- Correction plane: horizontal and vertical
- Correction sampling rate: bunch spacing (~3MHz)

Bunch compressor system feedback example:



Observables:

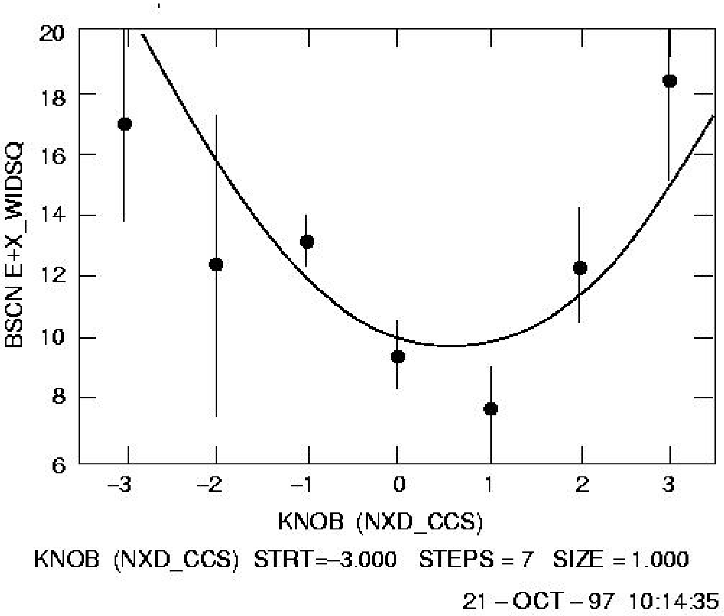
- Energy: E_0 (at DL1), E_1 (at BC1), E_2 (at BC2), E_3 (at DL2)
- CSR power   bunch length: $\sigma_{z,1}$ (at BC1), $\sigma_{z,2}$ (at BC2)

Controllables:

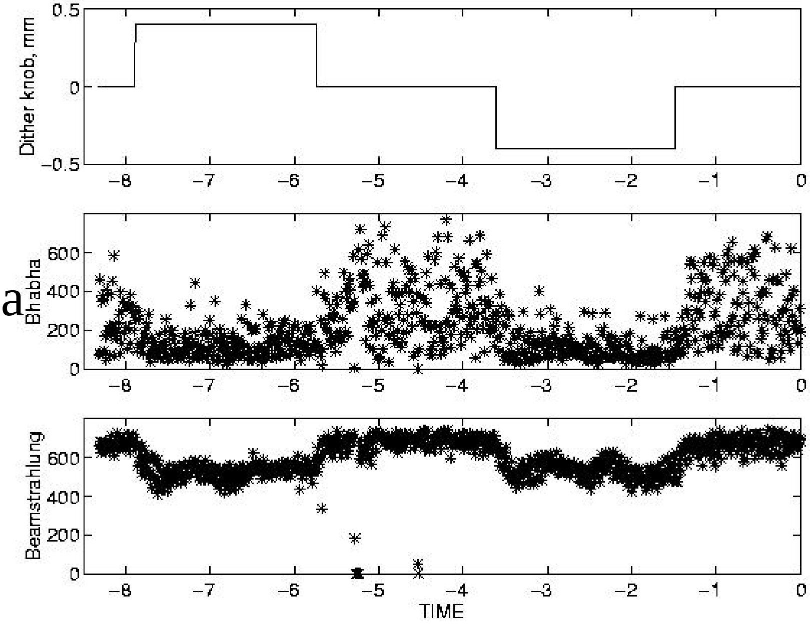
- Voltage: V_0 (in L0), V_1 (in L1), V_2 (effectively, in L2)
- Phase: φ_1 (in L1), φ_2 (in L2), φ_3 (in L3)

Luminosity Optimization in the SLC:

Original Scan method: Minimize beam width-squared from deflection scans (subject to meas error ~20-40% luminosity)



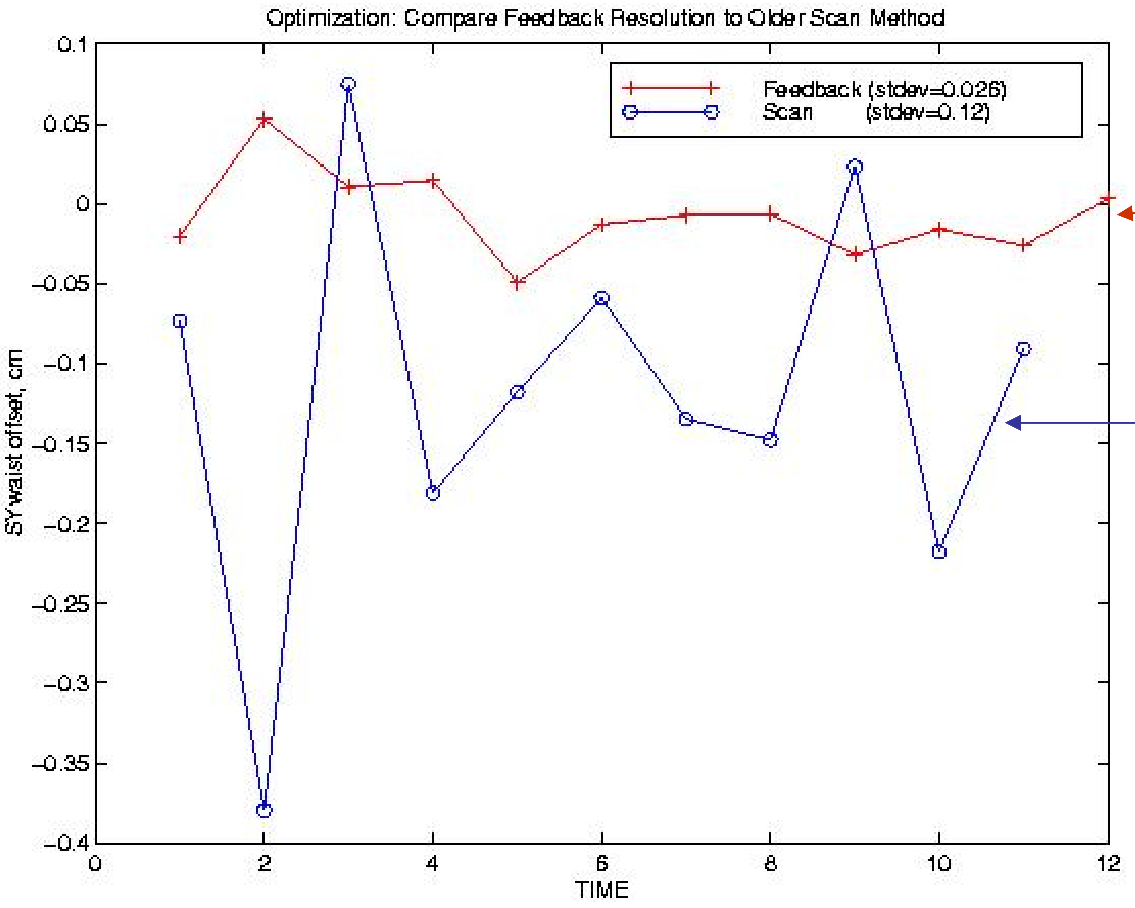
Dither Method: Maximize luminosity while moving multiknob up and down by small amounts, average 1000’s of pulses



Bhabha

BSM

Luminosity Optimization in the SLC: Comparative Resolution of Scan Method vs Dither Method

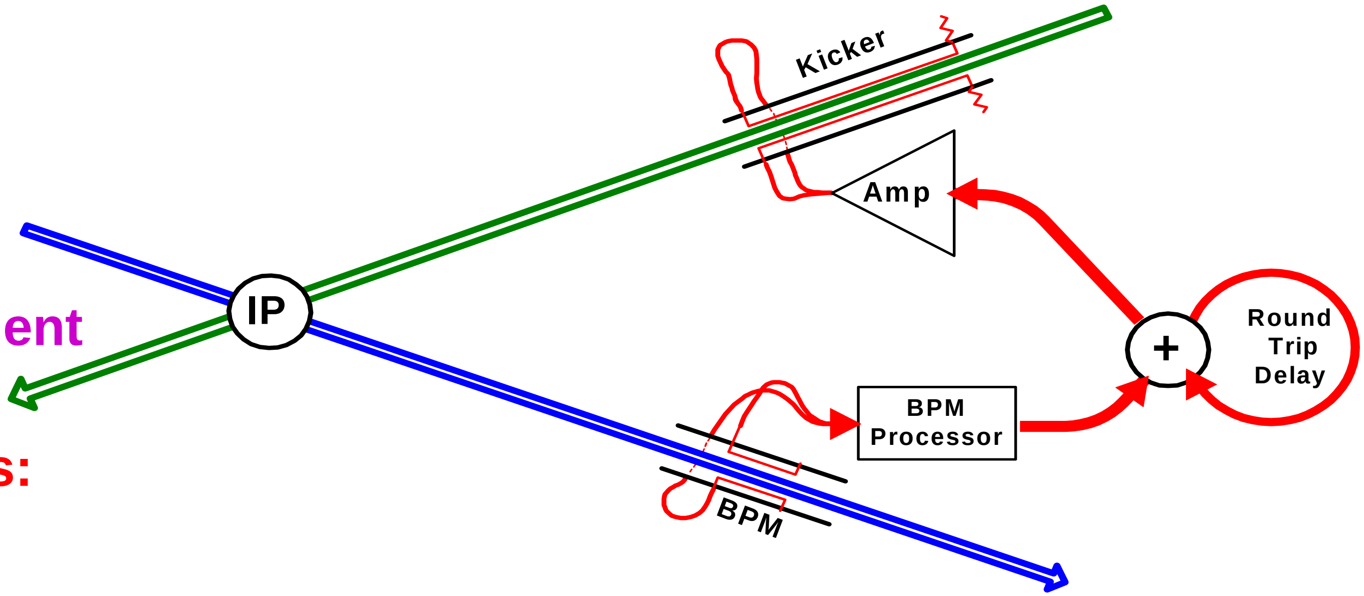


Dither

Scan

Intra-train Beam-based Feedback Concept

- Intra-train beam feedback is last line of defence against relative beam misalignment



- Key components:
- Beam position monitor (BPM)
- Signal processor
- Fast driver amplifier
- E.M. kicker
- Fast FB circuit

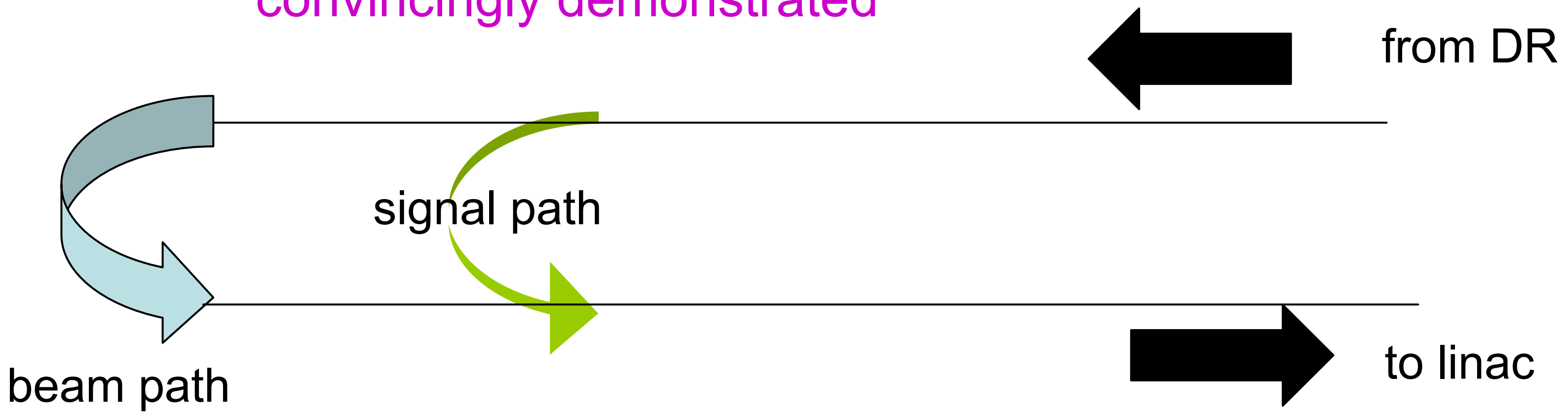
TESLA TDR: principal IR beam-misalignment correction

interaction between intra-train feedback loops

- Intra-train loops
  - interaction region steering → this is the most vital one
  - damping ring coupled bunch feedback → stability criteria
  - beam crossing ‘timing’
    - the phase of the bunch compressor (RTML) will require correction based on IP timing difference signals
    - latency is ~ 100 us
  - beam energy
    - These will be slower
  - damping ring extraction steering
- These can interact and ‘oscillate’

Feedforward

- If the the error signal can overtake the process itself, feedforward can be used.
  - very valuable – feedforward can improve stability with no latency
  - used with lasers; improvement is 10x at best
  - 3 x improvement typical.
- this is done with a ‘hairpin’ loop at the exit of the damping ring
  - accelerator based steering feedforward has not been convincingly demonstrated



from DR

signal path

beam path

to linac

References

Many good references are found in: proceedings of the ‘Beam Instrumentation Workshop (BIW)’ published by AIP. First two listed are from 1996; ANL BIW.

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3. W.H. Press et al, ‘Numerical Recipes in C’, Cambridge U. Press (1992) – full text available online free
4. John Irwin et al, ‘Model Independent Analysis’
5. Ron Akre, Paul Emma, et al., ‘A Transverse RF Deflecting Structure for Bunch Length and Phase Space Diagnostics’, SLAC-PUB-8864, 2001.
6. Tom Himel, ‘Feedback: Theory and Accelerator Applications’, SLAC-PUB-7398, 1997.

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7. Tom Mattison, ‘Optical Interferometer Vibration Control’, ALCPG meeting Victoria, BC, 2004.
8. T. Shintake, Nucl.Instrum.Meth.A311:453-464,1992