Diagnostics for Free Electron Lasers

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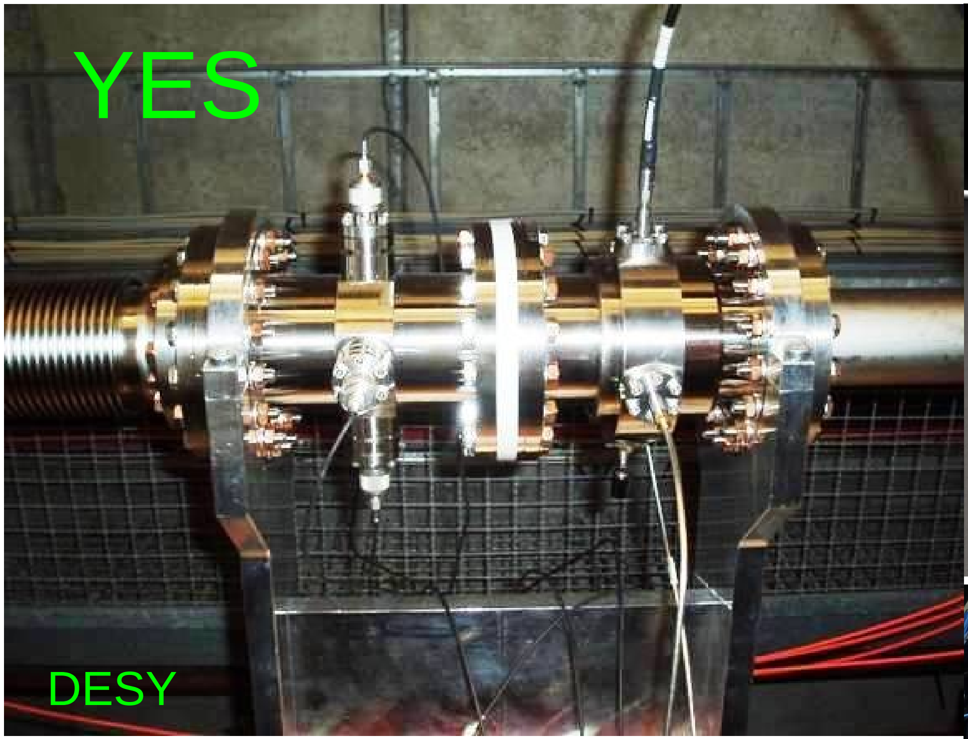
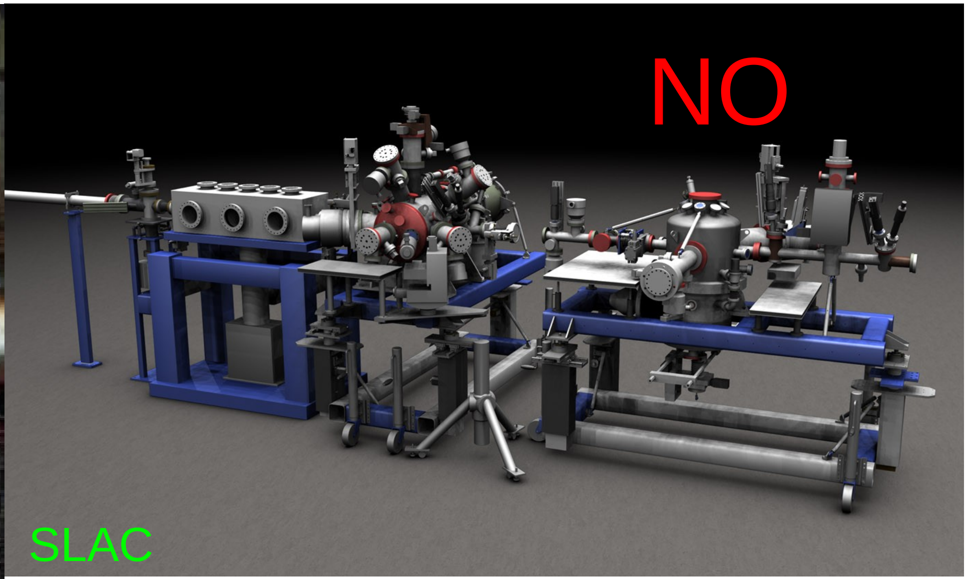
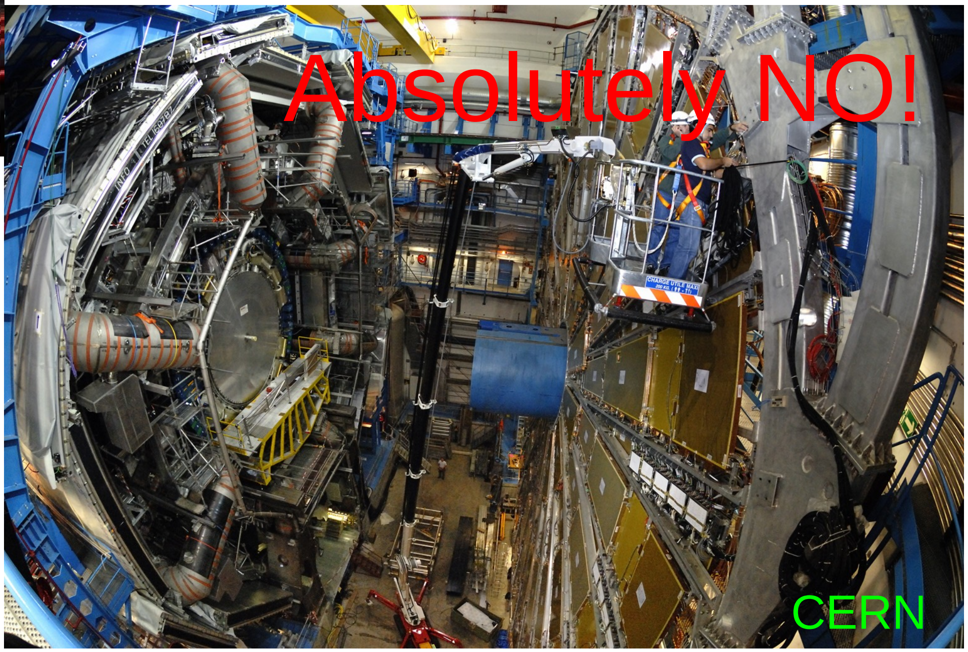
“Were you involved with LCLS lasing or did you only do the diagnostics?”

- Can't construct a FEL with sufficient accuracy to allow it to lase when you turn it on
  - Quads would need few-micron alignment over 100s of Meters
- Diagnose hardware problems in the FEL system
  - Magnet with bad multipole components.
- Understand new “physics”
  - COTR emission from profile monitors

A Diagnostic is *NOT* an Experiment







Diagnostics need to be simple and reliable.

Usable by operations staff

Diagnostics Covered Here

- RF-based electron beam centroid
  - Beam Position, Bunch Arrival Time
- Transverse and Longitudinal profile
  - Fluorescent screens, OTRs, wire scanners, Transverse cavities,
- X-ray profile
  - Fluorescent screens
- X-ray pulse energy

Lots of things NOT covered here

Why RF Instrumentation?

- Electrons couple through electromagnetic interactions

- Electromagnetism is linear

- Coupling to the beam is nearly non-invasive

Amplifier

Complx RF devices are very common

Beam couplings are large:
1nC, 1ns, 100 Ohms -> 0.1 uJ.

Thermal Noise is $k_b T = 4\times10^{-21}$J

Signal to noise ~2×10^{13} in power
Or 5×10^{6} in voltage

Cheap and Good!
50KHz – 4 Ghz \$1.45

Added noise 20% of room temperature thermal
(noise temperature = 60K)

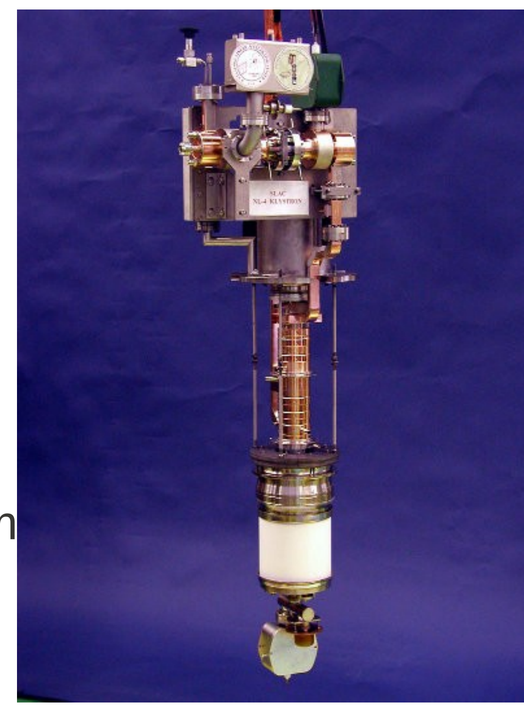
Intro to RF – Units / Signal Levels

"Bands" - basically random letters assigned to frequency ranges
L = 1-2 Ghz, S = 2-4 Ghz, C = 4-8 Ghz, X = 8-12 GHz

Impedances: Most RF systems use 50 Ohm cables

DBm = Decibel milliwatt = $10\log_{10}(1000P)$ with P in Watts.

0dBm = 1 mW = 224mV RMS into 50 Ohms
Typical low level RF signal



20dBm = 100mW = 6 volts peak to peak is the maximum signal level in typical low level RF systems

Thermal noise = -174dBm in a 1Hz bandwidth

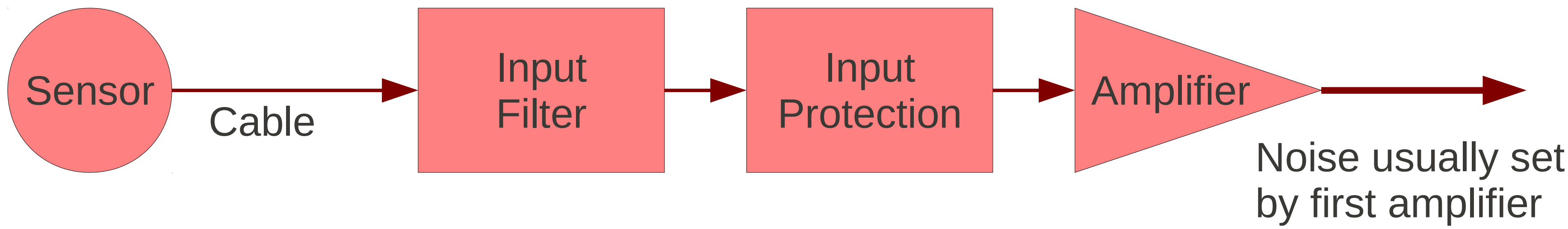
Typical accelerator diagnostic system bandwidth is 10MHz
Implies approx -100dBm noise levels (10^{-13} Watt, 2 uV RMS).

Note that high power RF systems produce ~ 100MW = 110dBm
Range of RF signal levels is 210dB! (10^{21})

Noise in RF Systems

"Noise Figure" is the ratio of the system noise (reference to the input of the circuit) to ideal thermal noise.

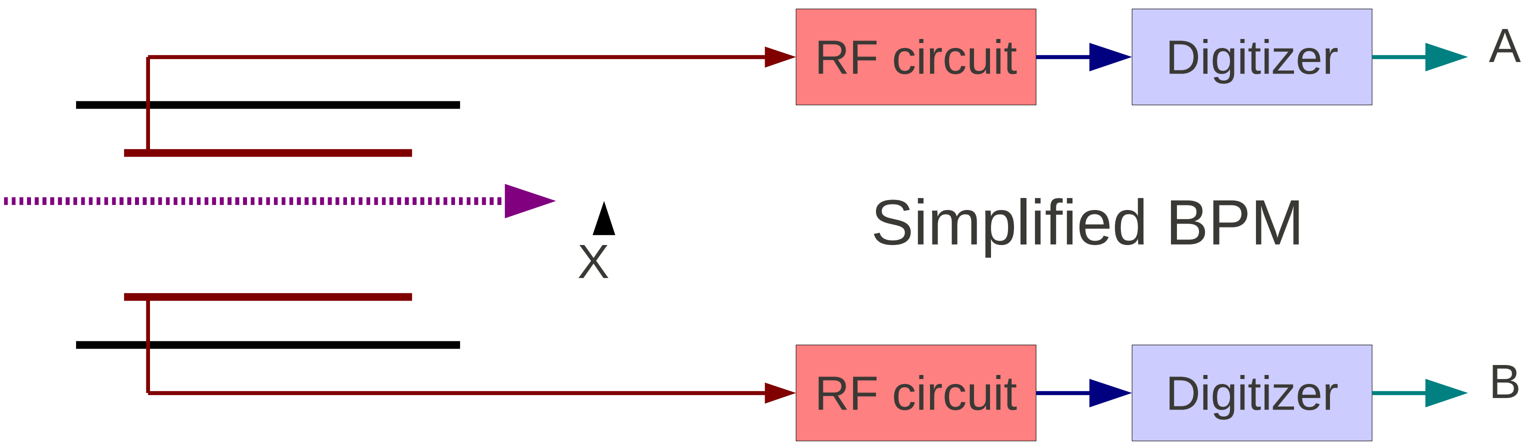
A 10dB noise figure implies that the circuit is 10X noisier (in power), than an ideal (room temperature) circuit, or ~3X larger in amplitude noise



Noise is generally dominated by the lowest level signals in the RF system.

For most well designed RF systems, losses in the input cable, filters and protection circuitry are a few dB.
The noise figure on RF pre-amplifiers is usually < 3dB
Generally safe to assume a noise figure < 10dB for a RF system.
(can usually do better than this)

Linearity in RF Systems



Simplified BPM

$$A = \alpha Q(D - X), B = \alpha Q(D + X) \rightarrow X = D\frac{B-A}{A+B}$$

Now if there is some nonlinearity in the response

$$A = A_0(1 - A_0/V_0), B = B_0(1 - B_0/V_0)$$

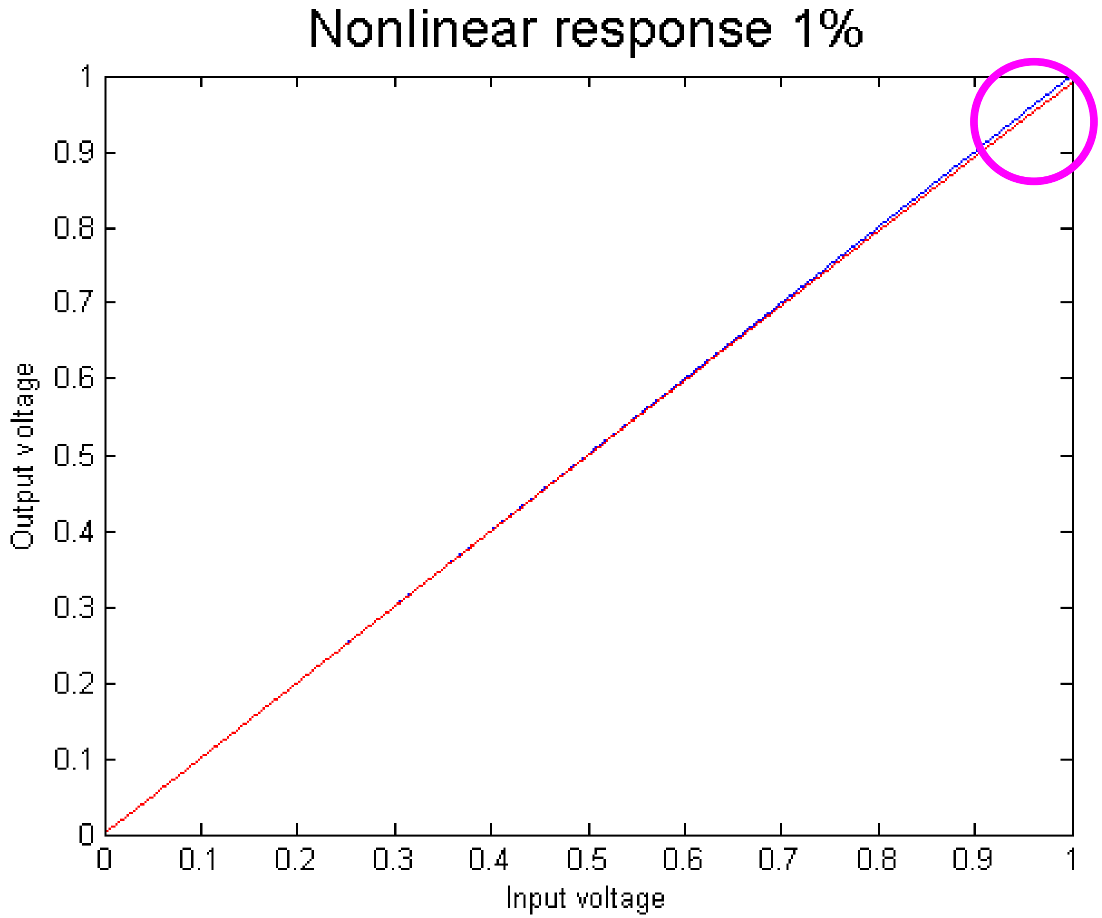
You end up with a measured output position that depends on the beam charge.

$$X = X_0 - X_0\frac{\alpha QD}{V_0}$$

For a 1 micron oribt accuracy at 1mm offset, need <0.1% nonlinearity over the expected charge range.

For a 10nm cavity BPM at 100 um offset, would need 10^{-4} nonlinearity. This is often the performance limit in this type of system

Measuring Linearity

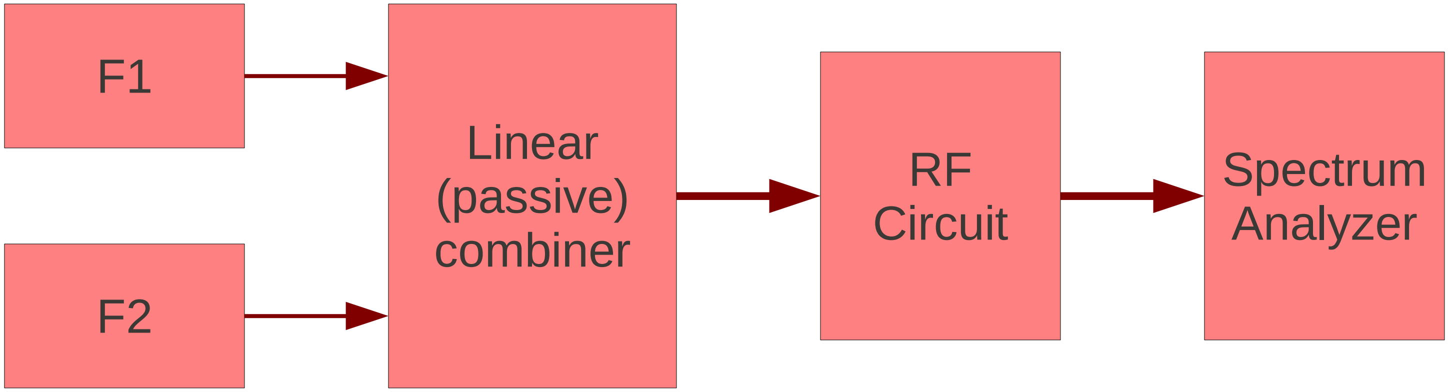


1% nonlinearity barely visible

In principal can measure nonlinearity varying input signal level and measuring the output.

This method is very sensitive to the accuracy of the measurement equipment an is difficult below 1% non-linearity

Measuring Linearity



Two frequency sources in a linear combiner will produce only the original frequencies

Any non-linearity in the test circuit will result in sum and difference frequencies.

$$A=\sin(w_1 t), B=\sin(w_2 t), Y=(A+B)+\alpha(A+B)^2+\beta(A+B)^3+\ldots$$

Second order term includes sum and difference frequencies

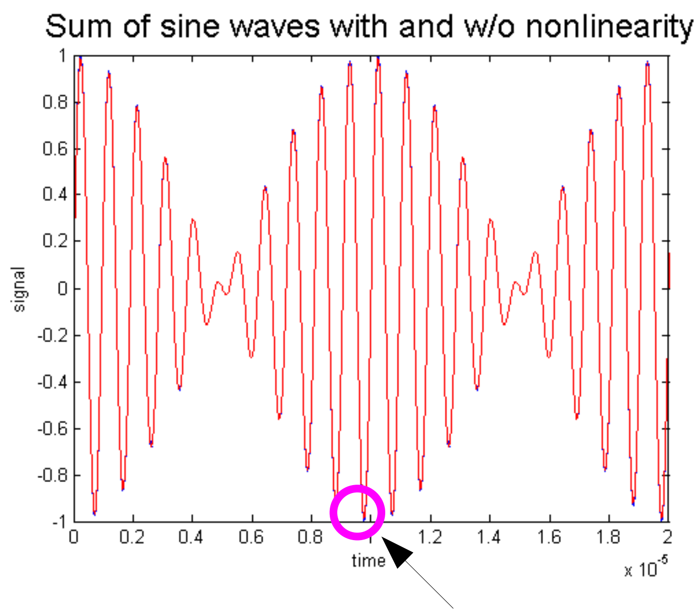
$$AB=\sin(w_1 t)\sin(w_2 t)=(1/2)(\sin((w_1+w_2)t)+\sin((w_1-w_2)t))$$

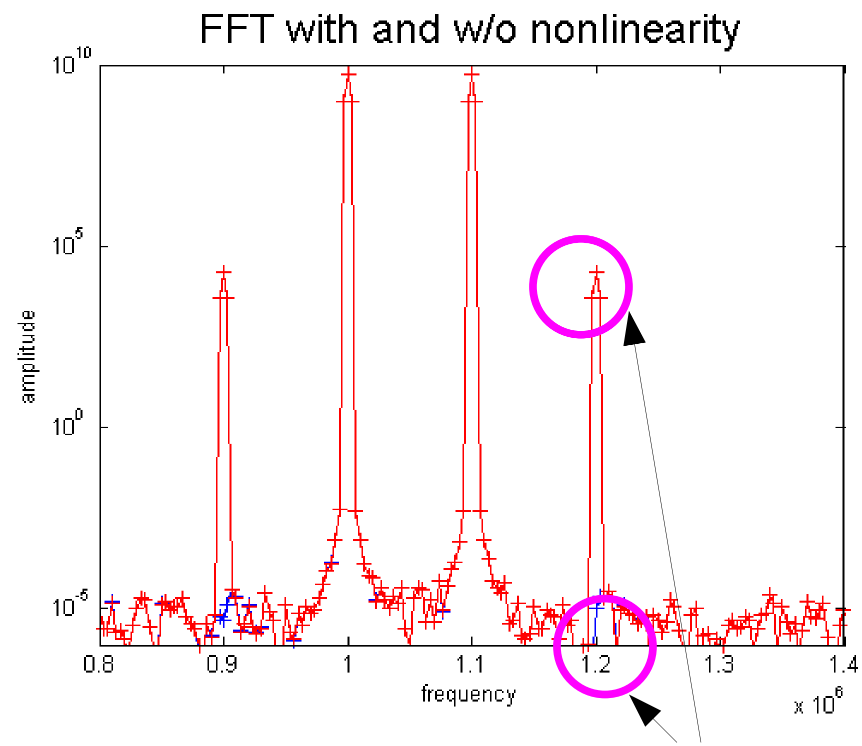
Third order term includes

$A^2 B=\sin(w_1 t)\sin(w_1 t)\sin(w_2)t$ Which includes $\sin(2\mathrm{w}_1-w_2)$ and $\sin(2\mathrm{w}_2-w_1)$

These sidebands can easily be seen on a spectrum analyzer

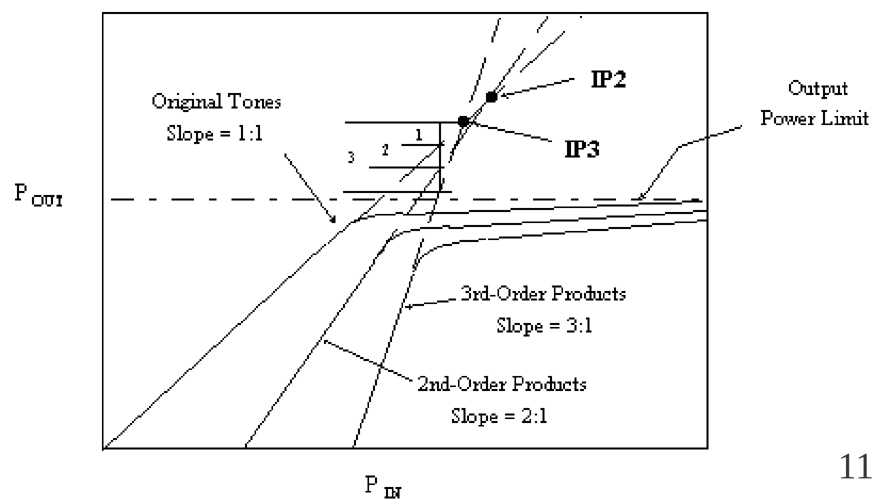
Non linearity: IP3





1% difference in raw signals
barely visible

Spectrum directly shows nonlinearity



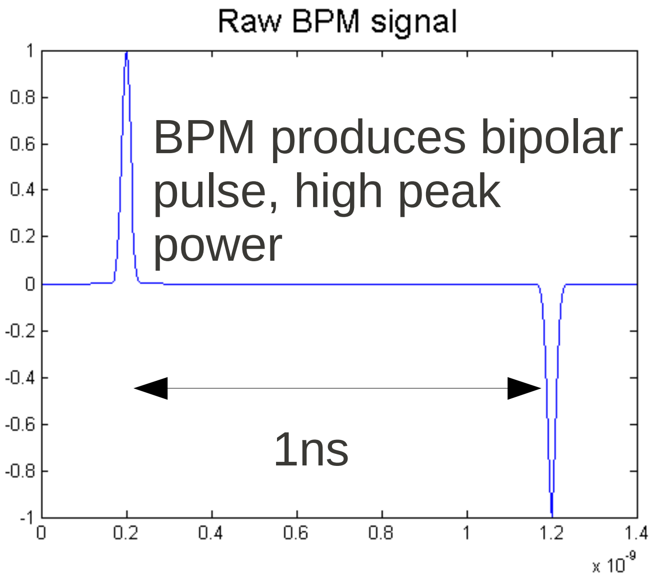
In most designs the 3rd order term is the most important because it produces frequencies near the signal frequency

The ration of 3rd order signal to fundamental is (in dB) 2X the ration between fundamental and "IP3" level

Non-linearity - Implications

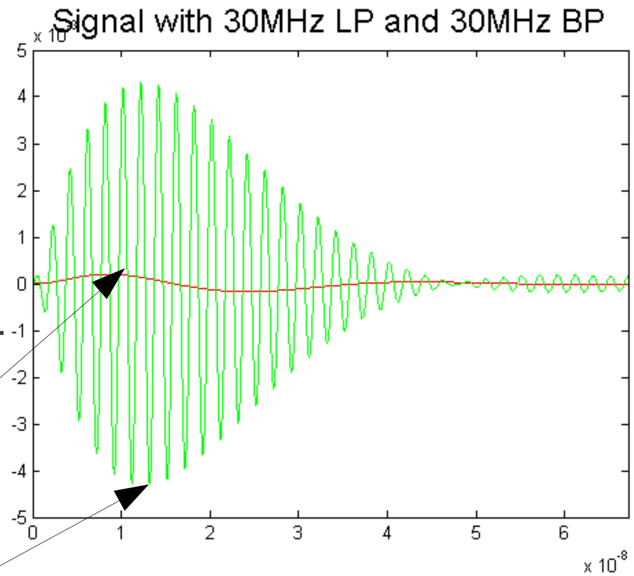
- Typical RF components have IP3 values from 15-45 dBm
- If you want 60dB linearity (0.1% in amplitude) you need to operate 30dB below the IP3.
- -10 to 15dBm typical
- Linearity is due to the largest signals the circuit may encounter.
- Linearity requires low signal levels, noise requires high levels: Circuit design is a compromise

Signal Filtering and Linearity

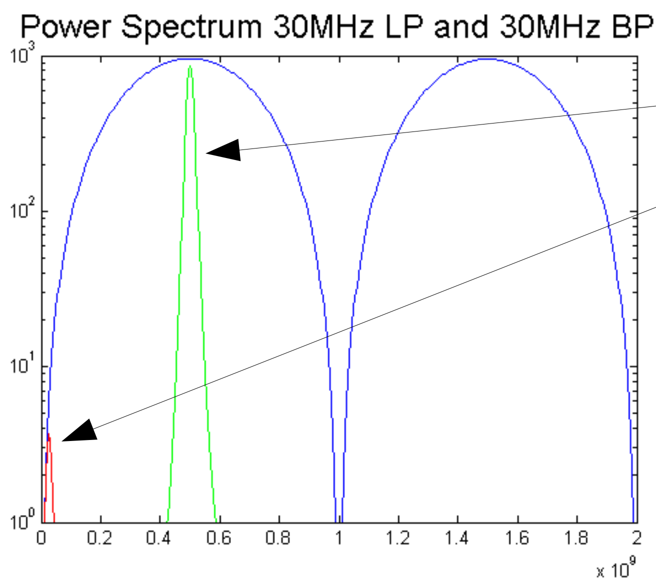


BPM produces bipolar pulse, high peak power

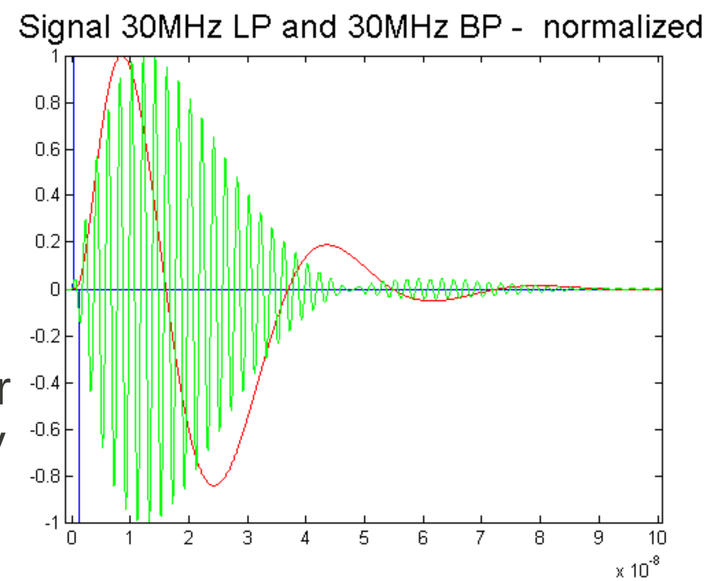
High power would cause linearity problems, so use a filter



Bandpass at signal peak is much more efficient than low pass



Filter bandwidth trades peak signal for total power – linearity vs noise tradeoff

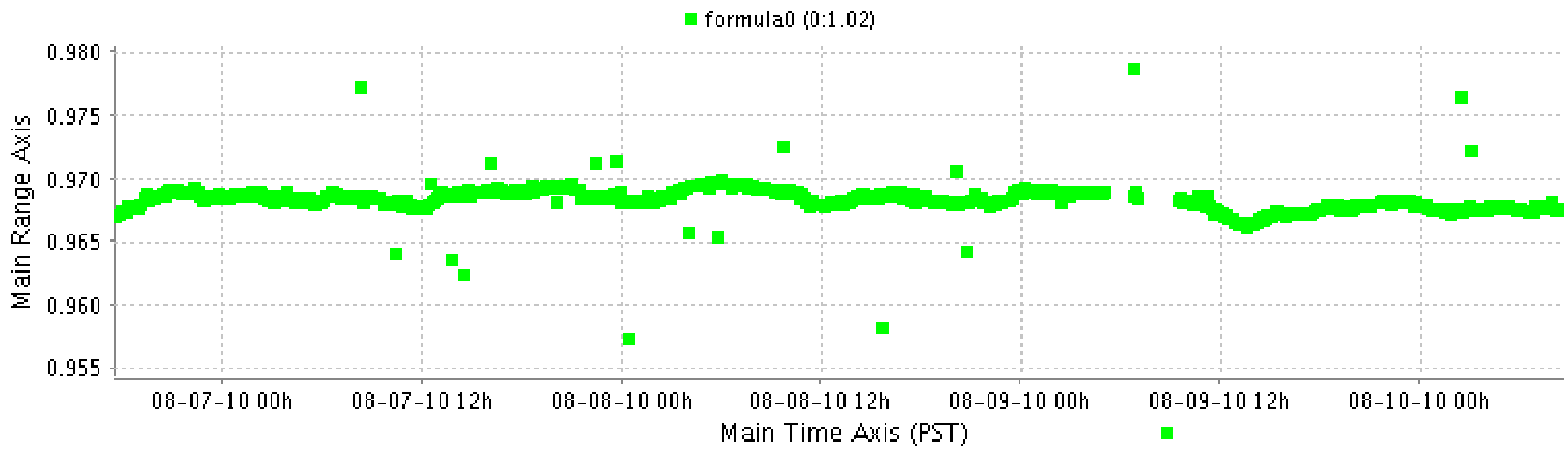


Gain and Phase Drift

For most BPM systems, changes in gain will result in changes in measured position.

Usually this scales with the BPM radius, for some designs scales with offset position

Typical RF amplifiers specified at 0.001 dB/C° to .01dB/C°, -> $2.3X10^{-4}$ to $2.3x10^{-3}$/ C°
Typical cable attenuation varies as $2x10^{-3}$/ C°
For a 1cm BPM, this is 2.3-23 microns / C°



RF system stability (ratio of charge measured by 2 phase cavity systems at LCLS) shows $3x10^{-3}$ stability for the entire system.
Temperature stability was < 0.1 C°

Frequency Conversion - Mixers

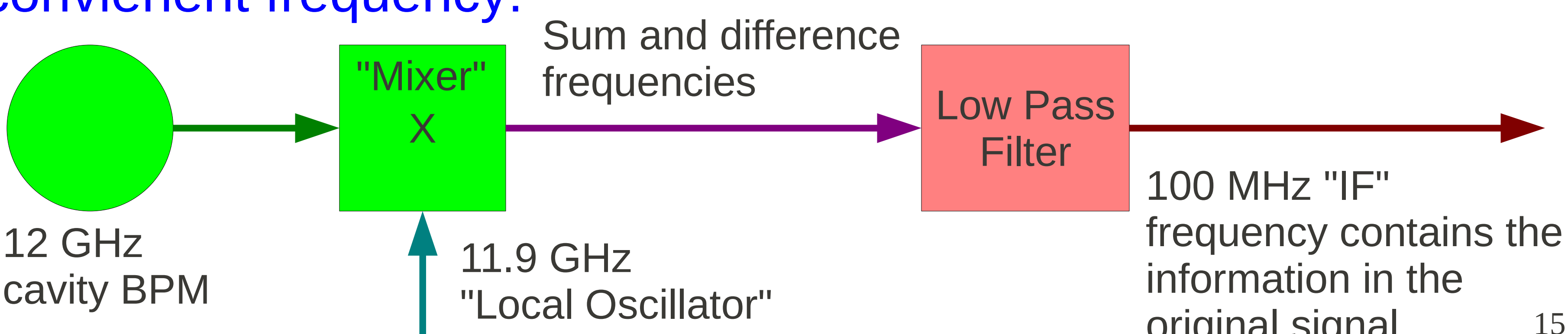
A non-linear combination of 2 signals will produce sum and difference frequencies:

$$A=\sin(w_1 t),\ B=\sin(w_2 t)\ Y=c_1 A+c_2 B+c_3 A^2+c_4 B^2+c_5 AB+\ldots$$

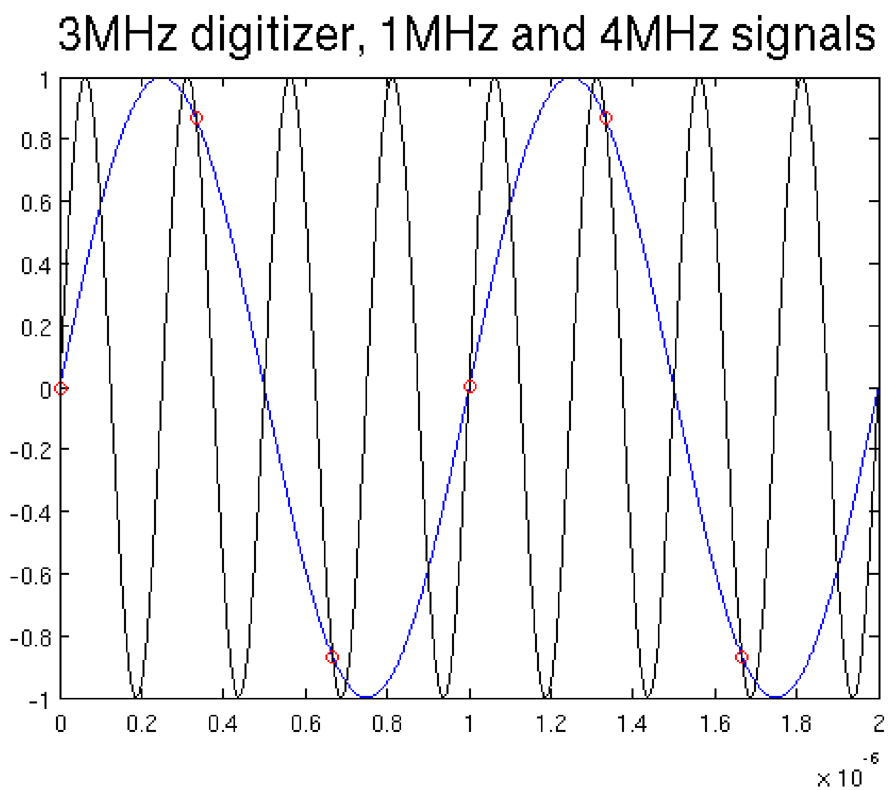
$$\sin(w_1 t)\sin(w_2 t)=\frac{1}{2}[\sin((w_1+w_2)t)+\sin((w_1-w_2)t)]$$

Term produces a difference frequency

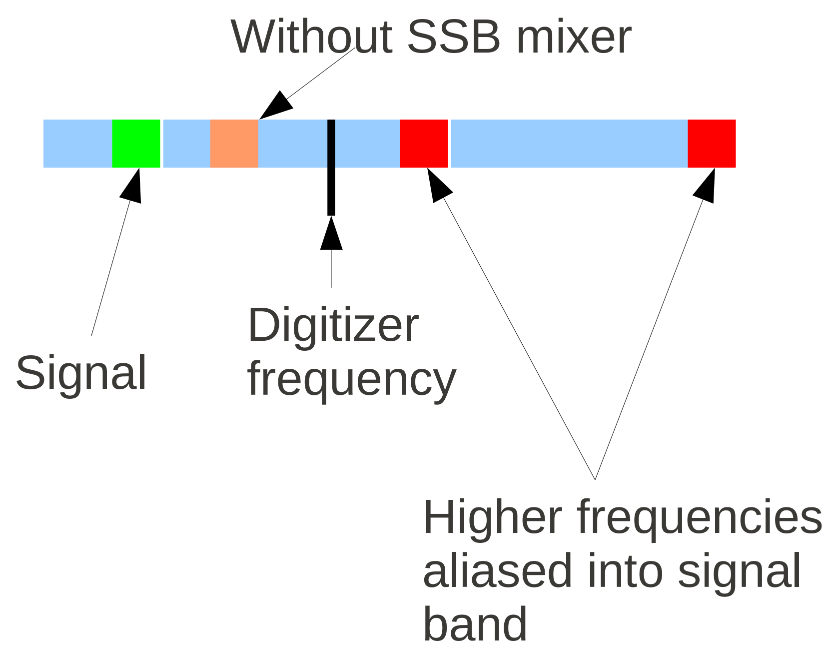
Used to shift the frequency of a narrow band signal to a more convienent frequency:



Digitizers, Bandwidth, Nyquist Limit



With a 3MHz digitizer, 1MHz and 4MHz are indistinguishable

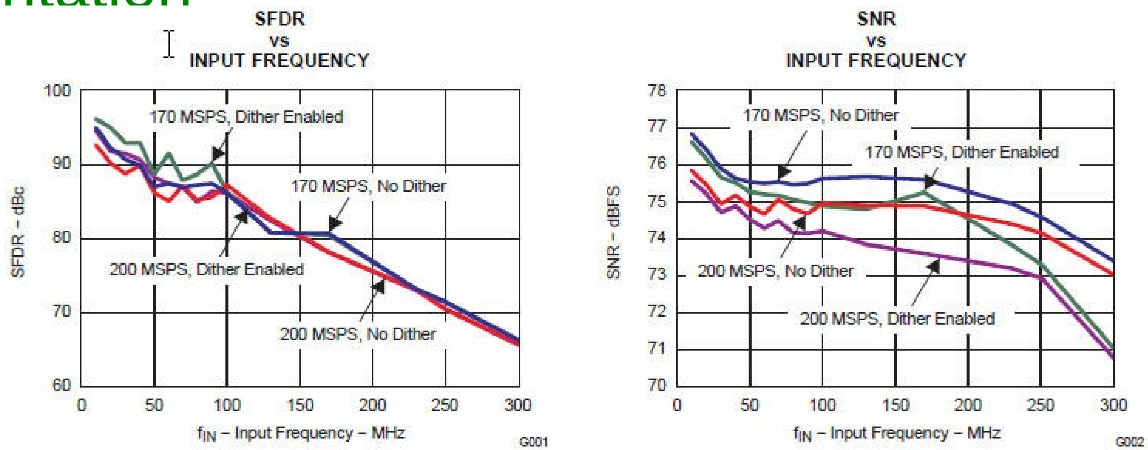


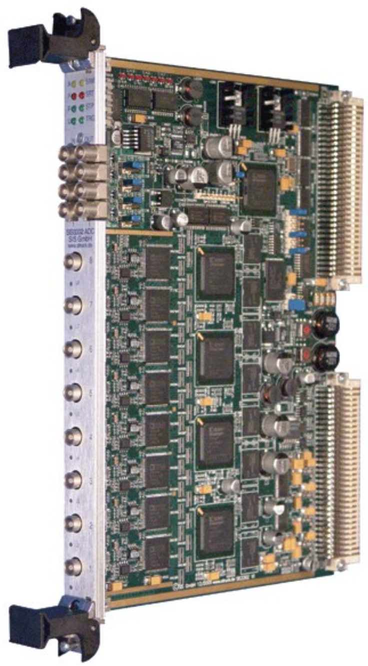
Without a bandpass filter noise will be aliased into the signal

For almost all digitizer applications an anti-alias filter is required

Digitizers

Remarkable progress in last 20 years has changed the approach to instrumentation





100Ms/s, 16 Bit 8 channel VME module

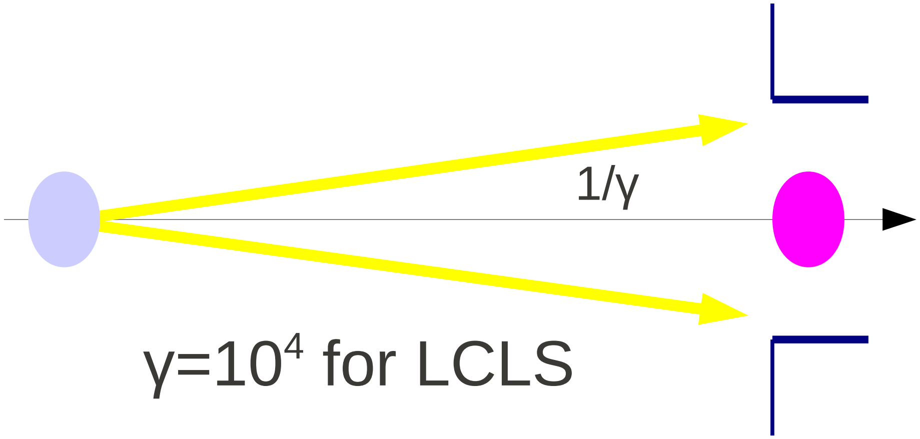
Digitizer chip from Texas Instruments ADS5485 200MS/s >75dB noise and nonlinearity for 100MHz input frequency $120/channel

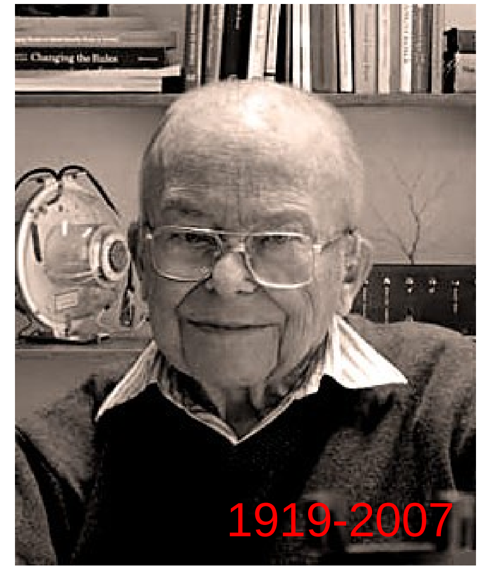
TI ADS5400 12 bit, 1 Gs/s with ~60dB dynamic range at 1.2 GHz input frequency. $750

Many modern digitizer chips have an input frequency > digitizing rate .Can make use a aliasing to measure higher frequency signals

"Modern" design: get the signal into a digitizer as soon as practical

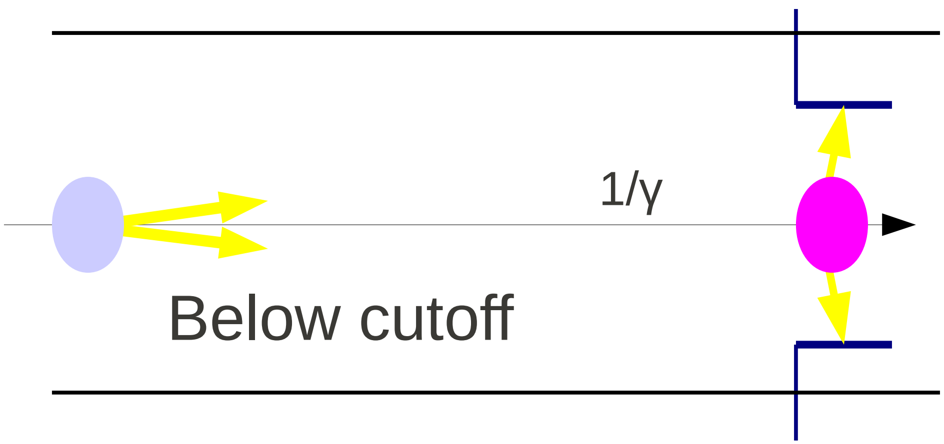
Beam Position Monitors





Pief Panofsky's question:

In an ultra-relativistic accelerator why doesn't the BPM measure the beam position hundreds of meters upstream?

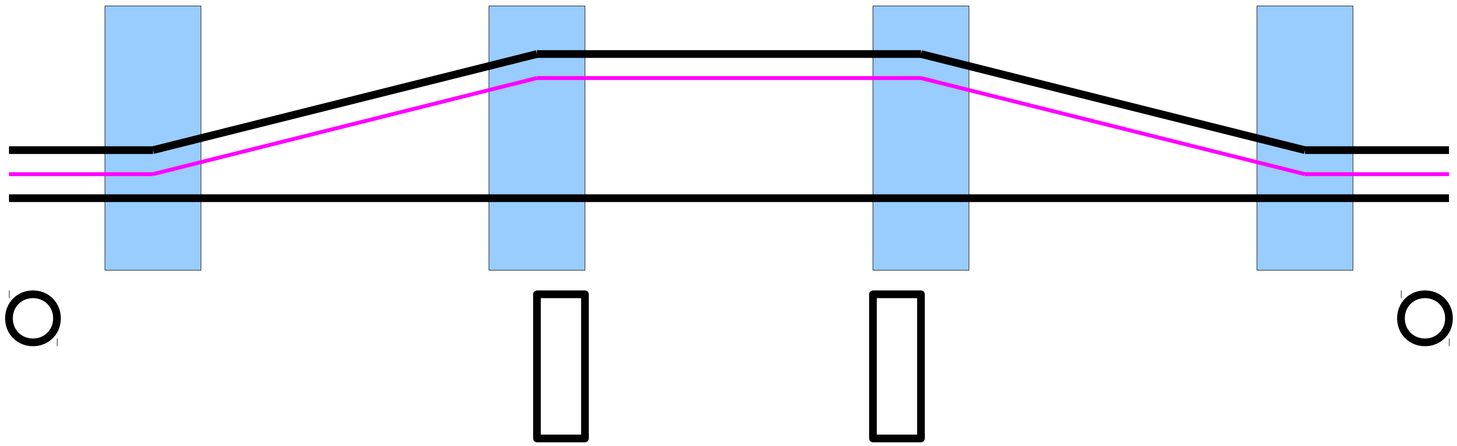


Beam pipe should be small enough to cut off the frequencies the BPM uses.

Signals can not propagate from upstream

Exactly where a BPM measures is still a tricky question

High Frequencies / Big Vacuum Chambers



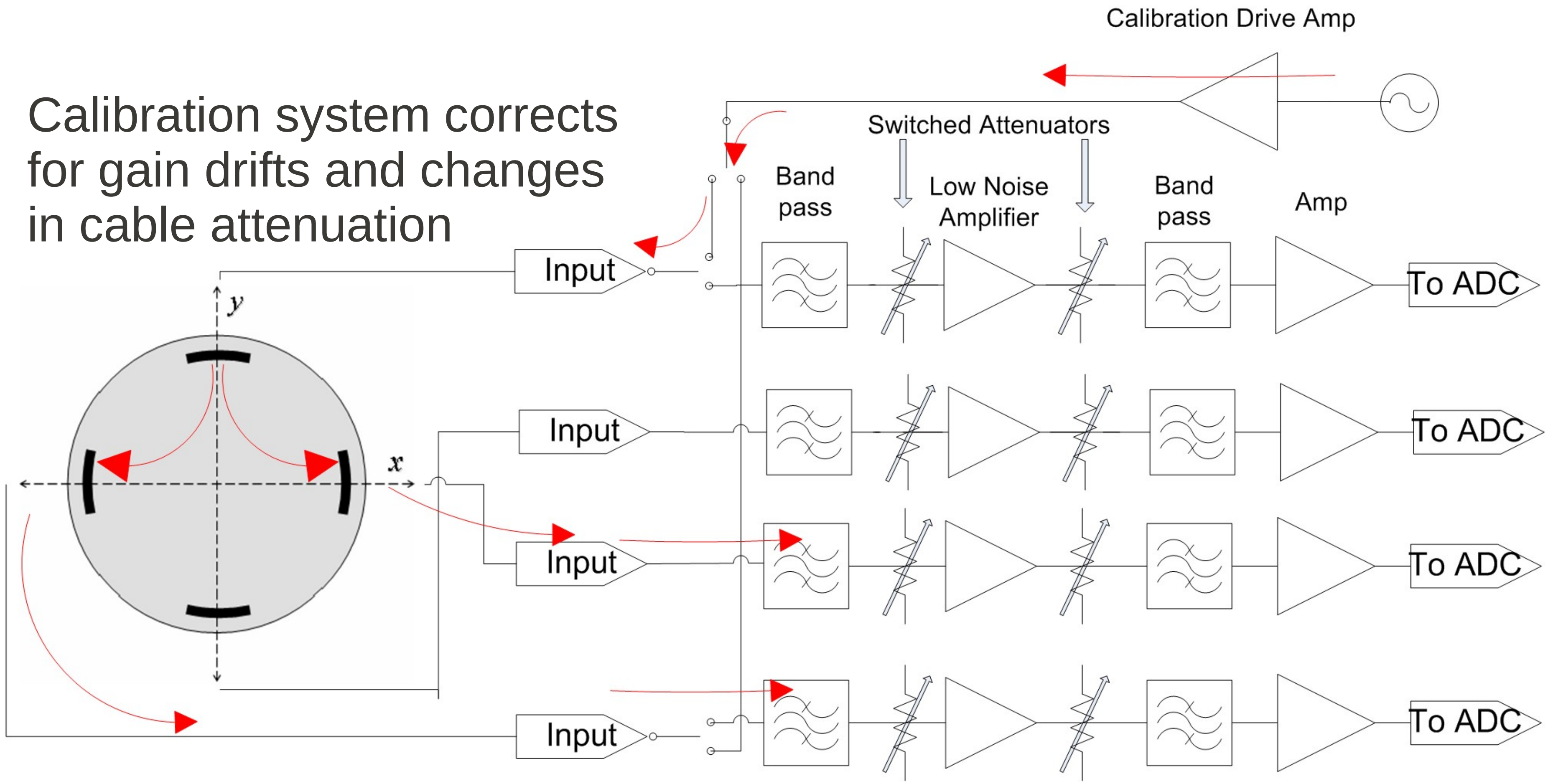
Compression chicanes with wide vacuum chambers can be a problem:

For LCLS BC2 would need a 50cm wide vacuum chamber -> cutoff frequency of 300MHz

Operation of a BPM above this frequency would be unreliable.
(actual LCLS design uses a movable chamber)

LCLS Stripline BPMs

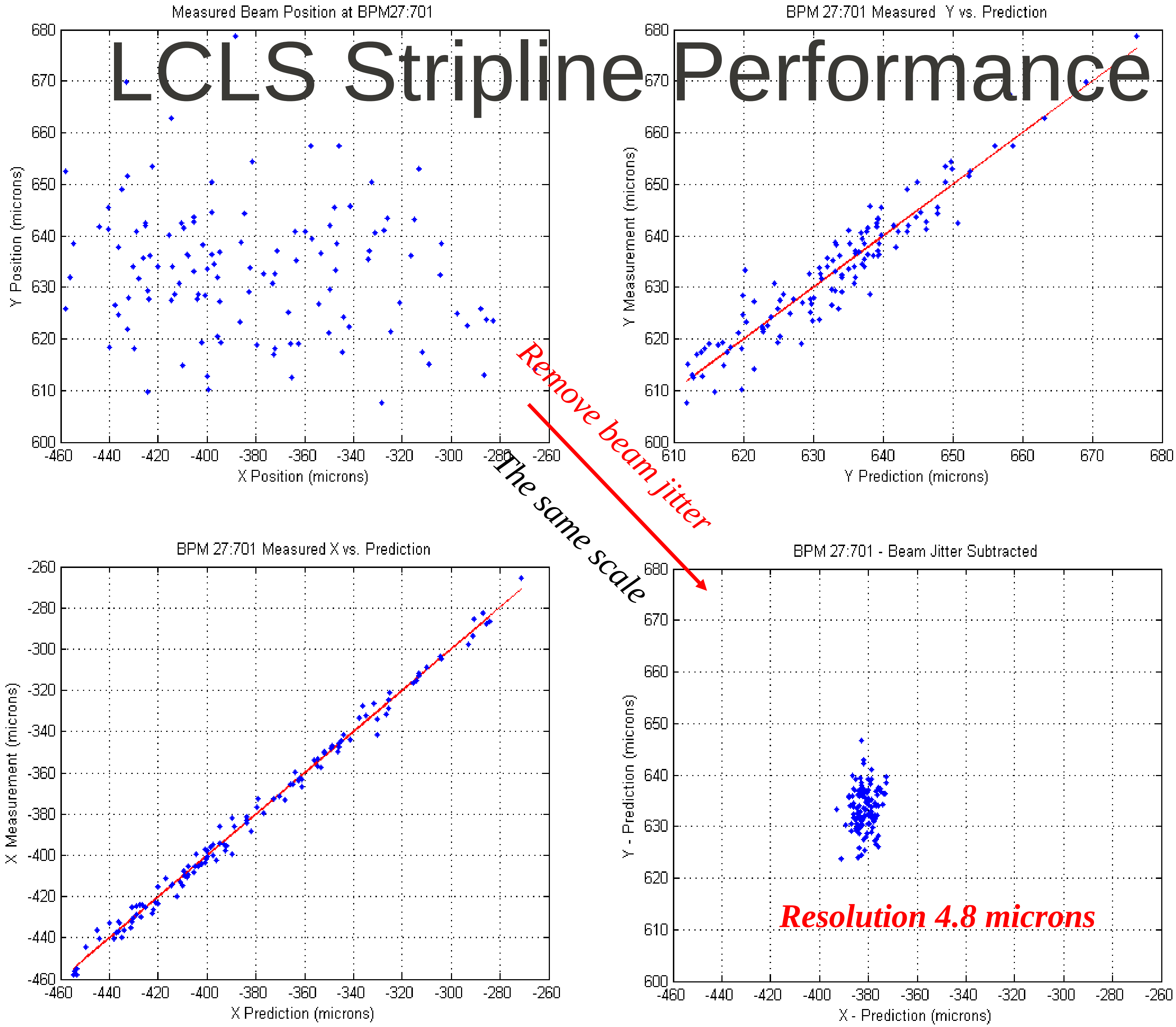
Calibration system corrects for gain drifts and changes in cable attenuation



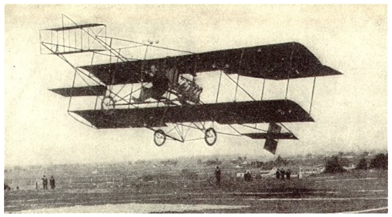
Calibrator pulsing tone to the Y+ stripline. ADC digitize X+ and X- signals.

R. Akre, E. Medvedko, R. Johnson, S. Smith, A. Young

LCLS Stripline Performance



Other BPM Processors



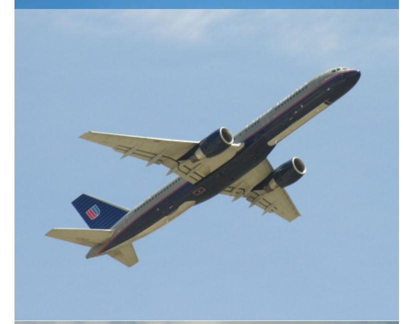

Tendency for early designs to explore a wide range of architectures, then gradually settle on an efficient design. (Dull but practical)

RF based BPMs have near theoretical noise for their input bandwidth, and have good linearity

Electronics cost is typically dominated by packaging, cables, etc.

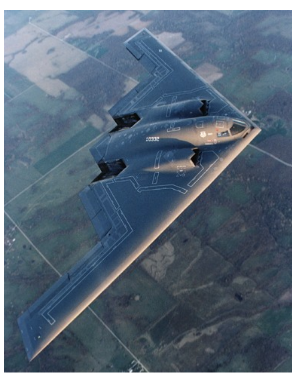
Alternate designs are interesting if they have increased bandwidth, or improved linearity.

Steve Smith: "Its amazing the efforts people will go to in order to avoid dividing two numbers in a computer"

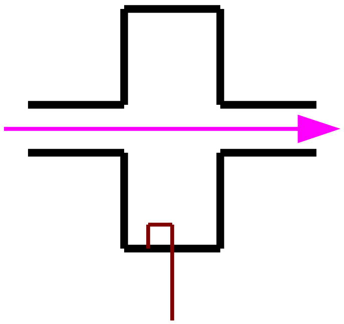
Alternate Stripline Processors

- Just put an amplifier and diode on each pickup
  - Very broadband (~20 GHz possible).
  - Linearity and stability likely to be very poor but high bandwidth makes calibration difficult
  - Might make sense for very low beam charges (but why not cavity BPM)
- Alternate filtering
  - Bandpass filter primarily used to stretch the pulse out in time, looses signal
  - Maybe a dispersive line to do the same thing without losing bandwidth?
  - Maybe frequency multiplex to many downmix circuits?
- BPMs for very high power beams may need an entirely different design

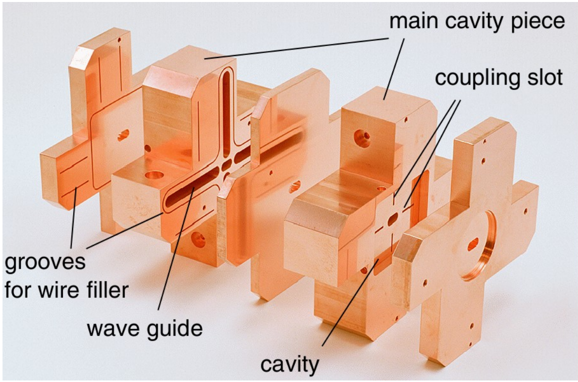


Sometimes unusual designs do make sense

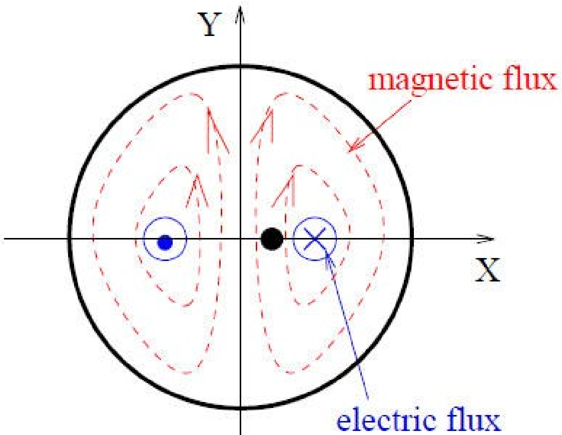
Cavity BPMs



Beam deposits energy in a resonant cavity. TM_{110} mode response is linear in position



Honda et al ATF2



V. Sargsyan

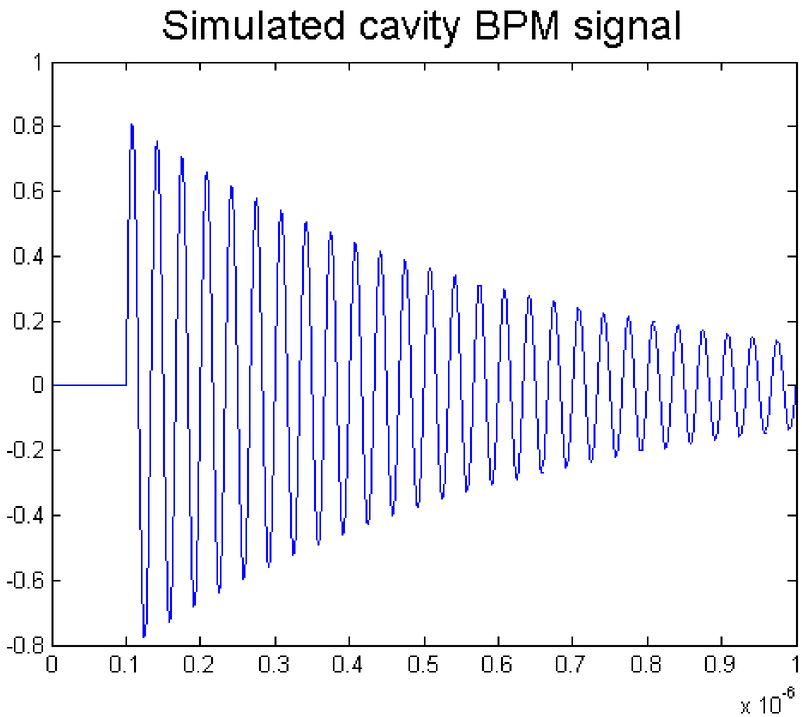
Operating frequencies typicall between 2.5 and 12 GHz

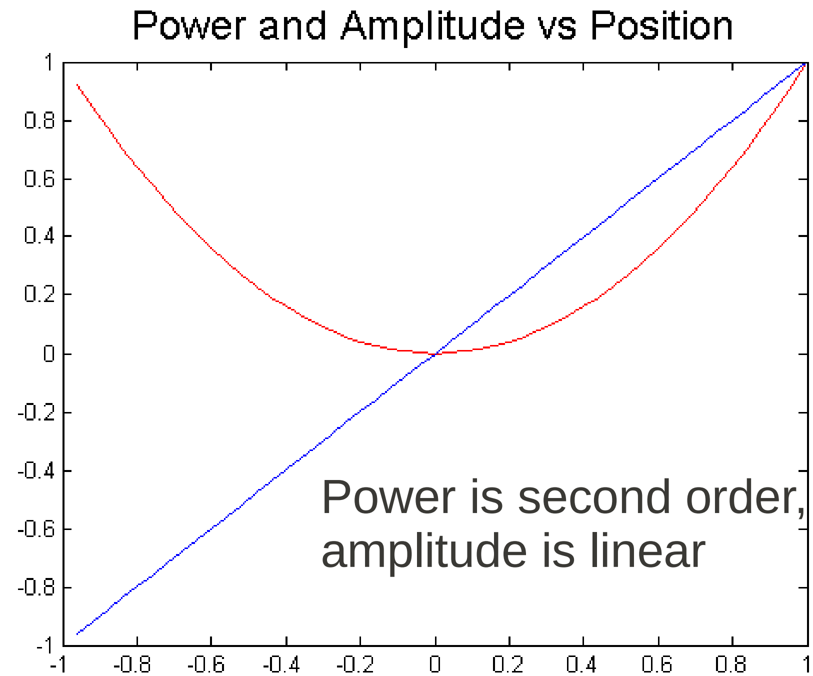
Energy coupled from beam to a cavity is similar to the energy coupled to a strip line

Cavity BPM "stores" the energy for a long time – don't need an external filter to fix nonlinearity.

Full deposited energy can be delivered to the electronics

Decoding Cavity BPM Signals

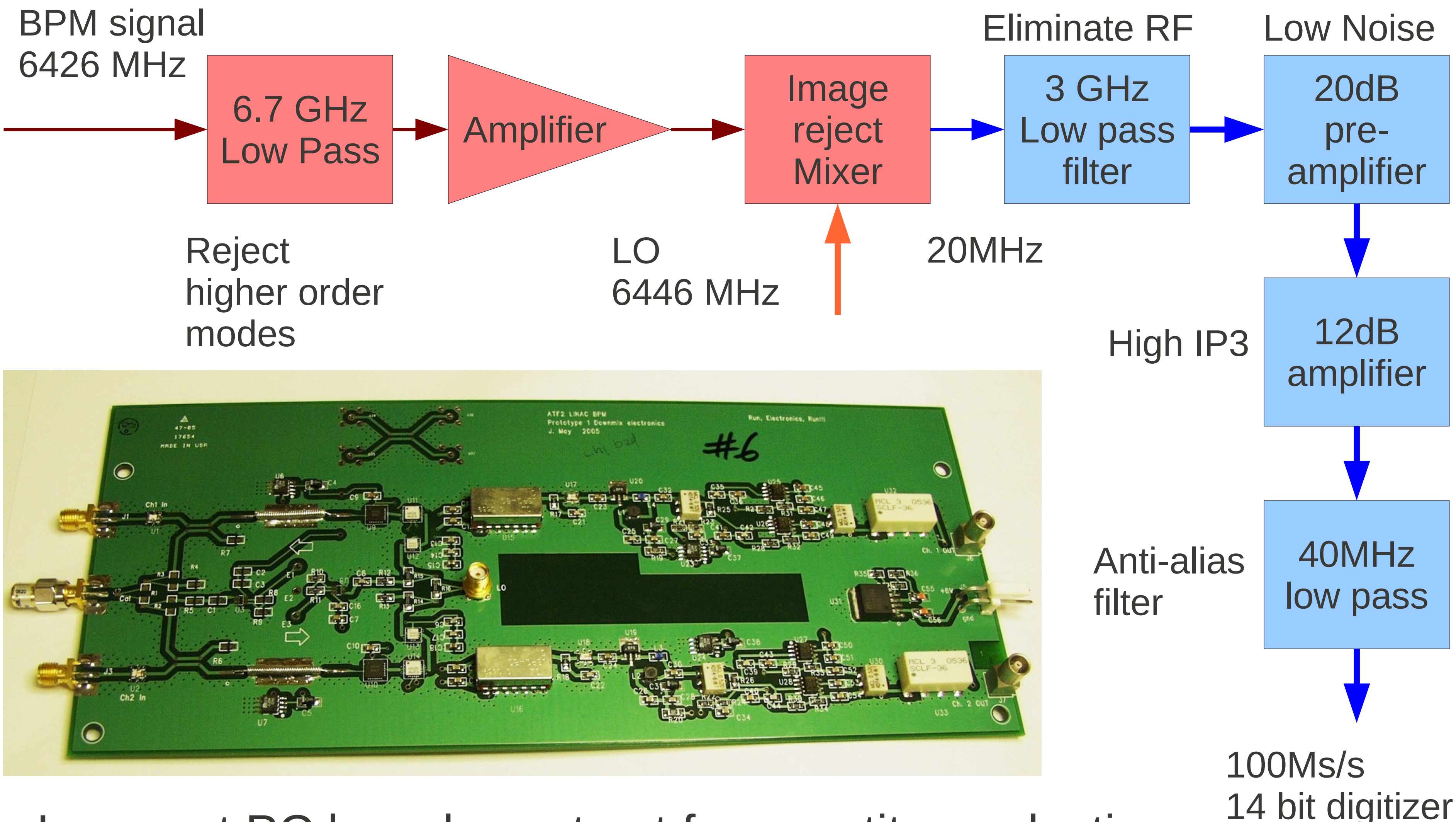




Beam pulse produces a decaying exponential.
Amplitude is linear in position and bunch charge
Can use reference cavity to normalize and define 0 phase.

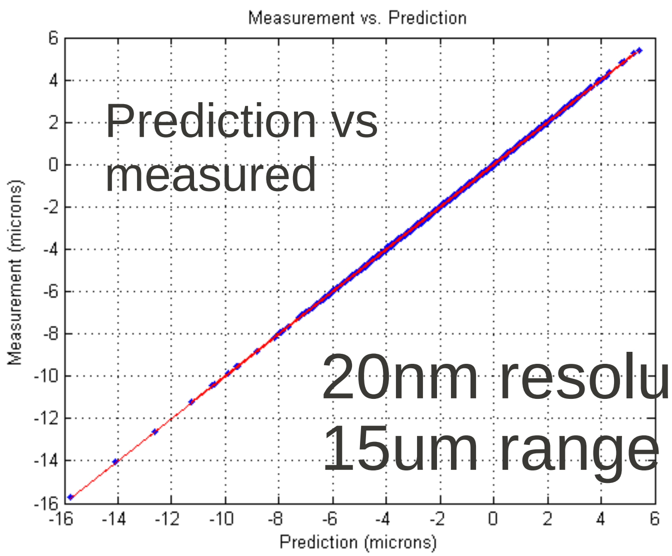
In general get better noise and linearity with a amplitude detection rather than power detection

Cavity BPM Electronics



Low cost PC board construct for quantity production
6dB noise figure, 70dB linearity measured
27nm RMS noise at ATF2

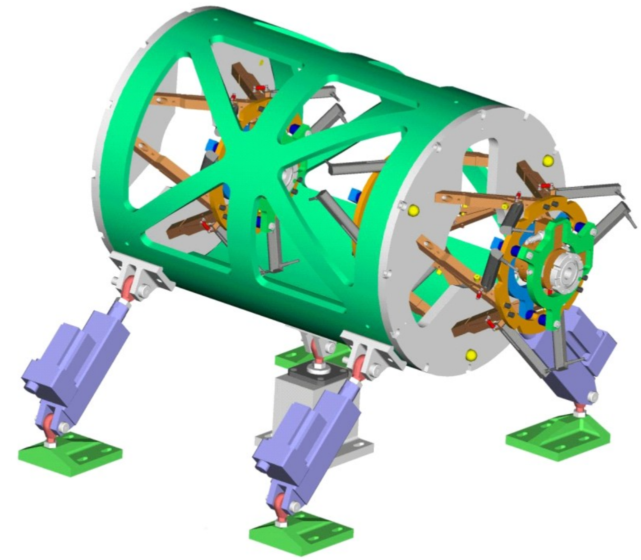
Cavity BPM Performance



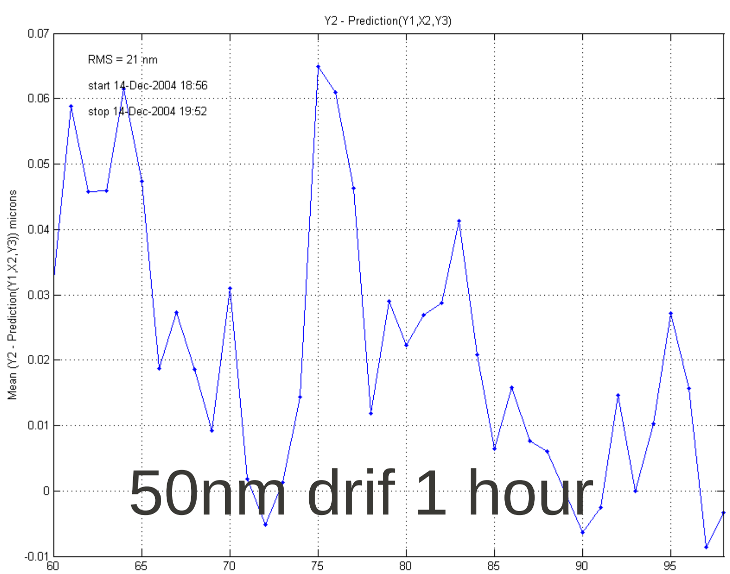
Prediction vs measured

20nm resolution
15um range

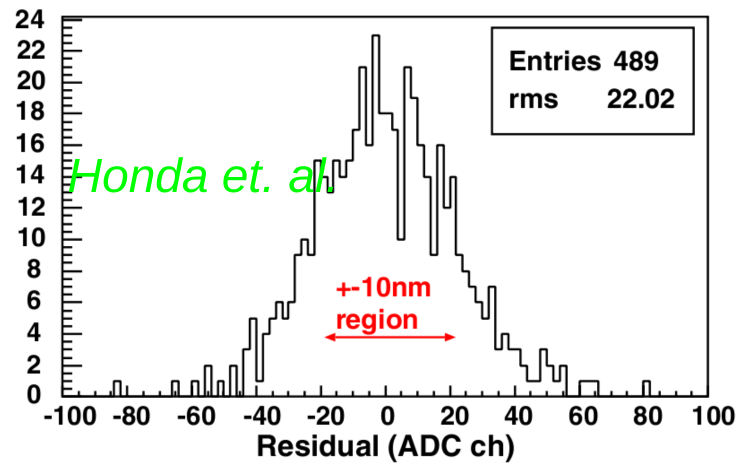
Use 2 BPMS to predict measurement of 3rd



LLNL cavity BPM support / mover system



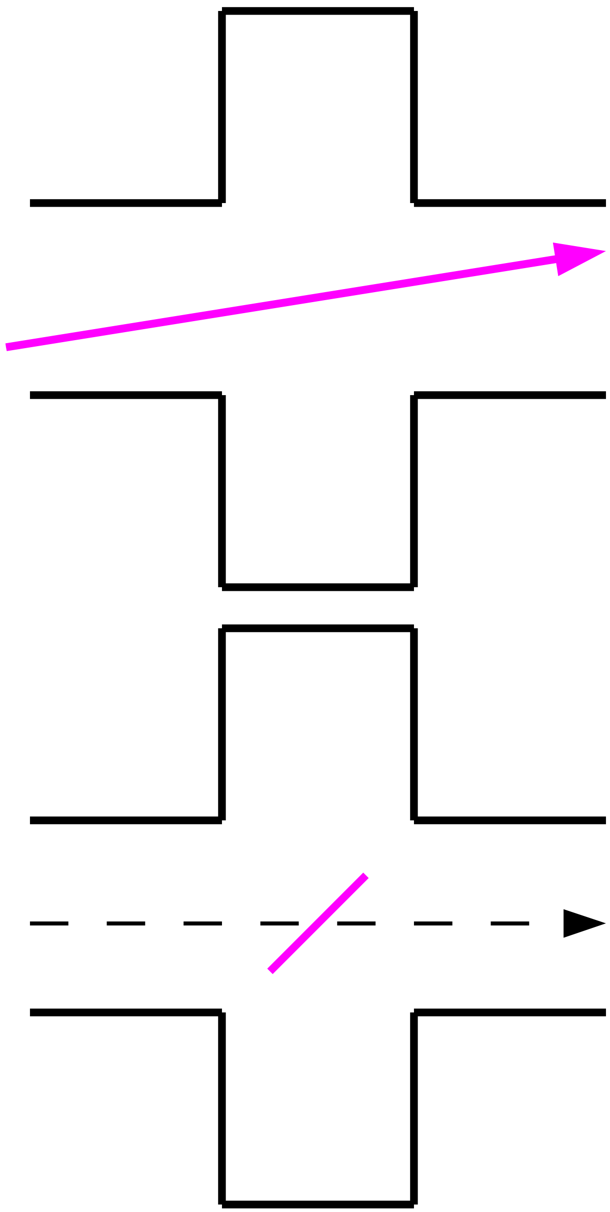
50nm drif 1 hour



Honda et. al

ATF2 I/Q BPM system with 10nm RMS noise

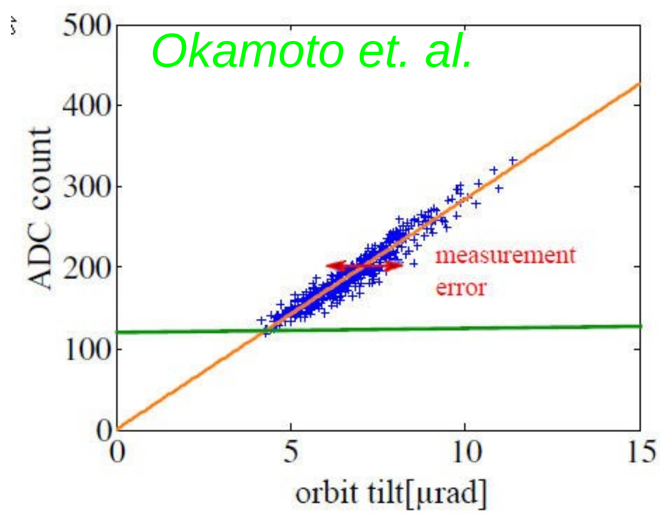
Beam Angle and Tilt Sensitivity



Cavity BPMs are sensitive to beam angle (whether you like it or not!)

Front of BPM sees one phase signal, back sees opposite phase, result with time delay is a 90° out of phase signal.

Amplitude scales as beam angle * cavity_length



360 nR resolution demonstrated at ATF

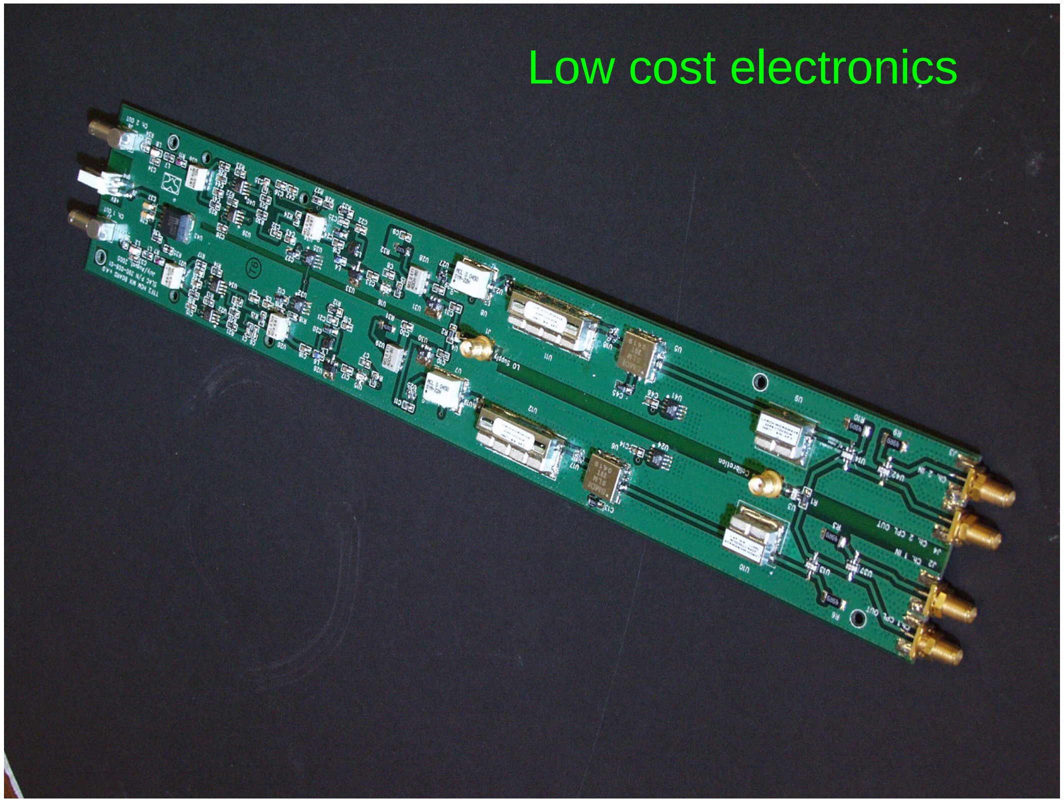
BPM is also sensitivte to bunch tilts.
Amplitude scales as head_tail_offset * bunch_length

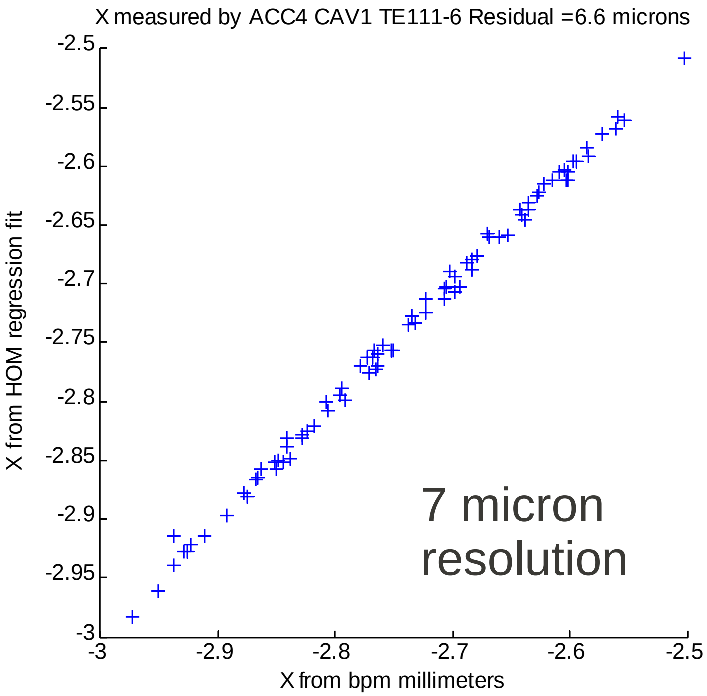
Typically a small effect for short electron beams used in FELs (demonstrated in KEK / ATF ring)

HOM mode BPMs for Superconducting Accelerators

Dipole modes act as "free" cavity BPMS.

System tested FLASH by SLAC / DESY collaboration.





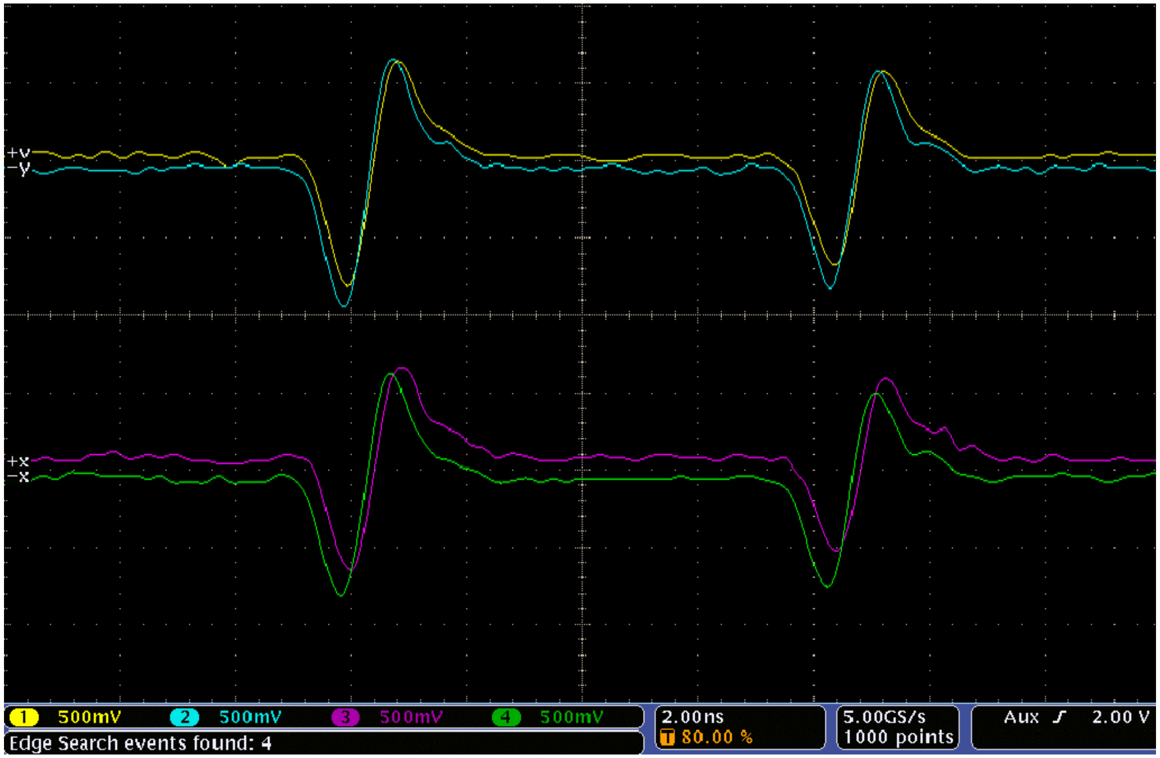
Limits to BPM Performance

- Theoretical thermal noise limit about 1nm for a 1nC bunch for a ~5 GHz cavity BPM
- Dynamic range
  - Better than 10^3:1 is difficult.
  - Can allow signal to saturate early in the RF pulse, then fit to decaying exponential
    - Tested at ATF2
- Mechanical mounting: 1 Meter, 1 C° is 10 microns for typical engineering materials!
  - Nanometer stability is a very challenging mechanical problem

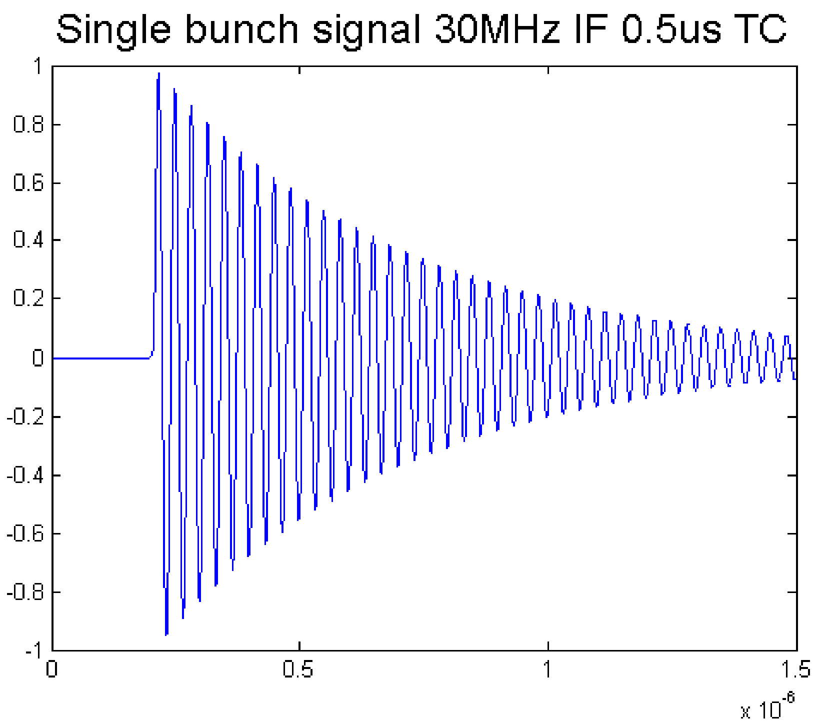
Multi-Bunch BPMs

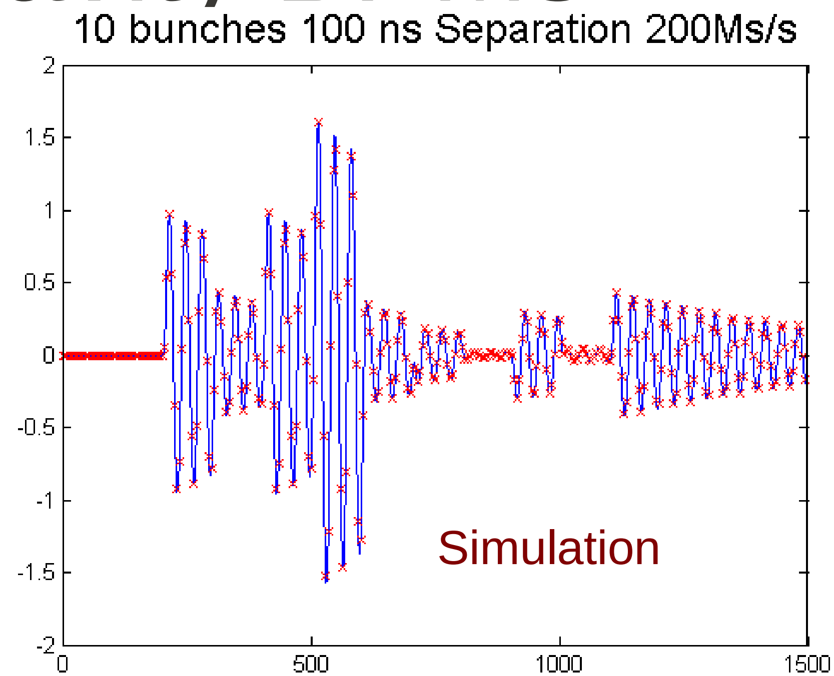
- For Stripline BPMs the pickup responds in ~ 1ns.
  - Filters used to improve linearity should have a time constant less than inter-bunch spacing
  - Digitizer must have a sample rate ~4X the inter-bunch spacing.
  - Small overlap between bunches can be fixed with proper calibration
- For cavity BPMs the situation is more complex

Stripline BPM trace: LCLS
2 bunch test.
8.4 ns bunch separation



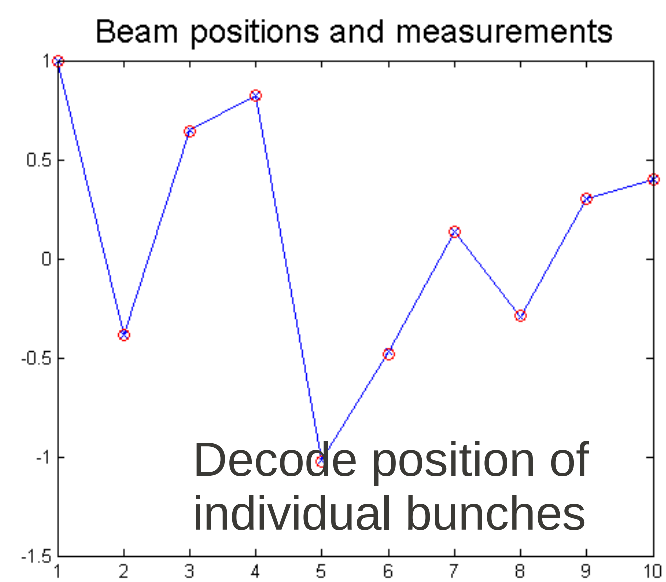
Multi-bunch Cavity BPMs





Signal between bunch N-1 and N used to predict signal between N and N+1.

Subtract and see only signal from bunch N



High / Low Q, Multibunch

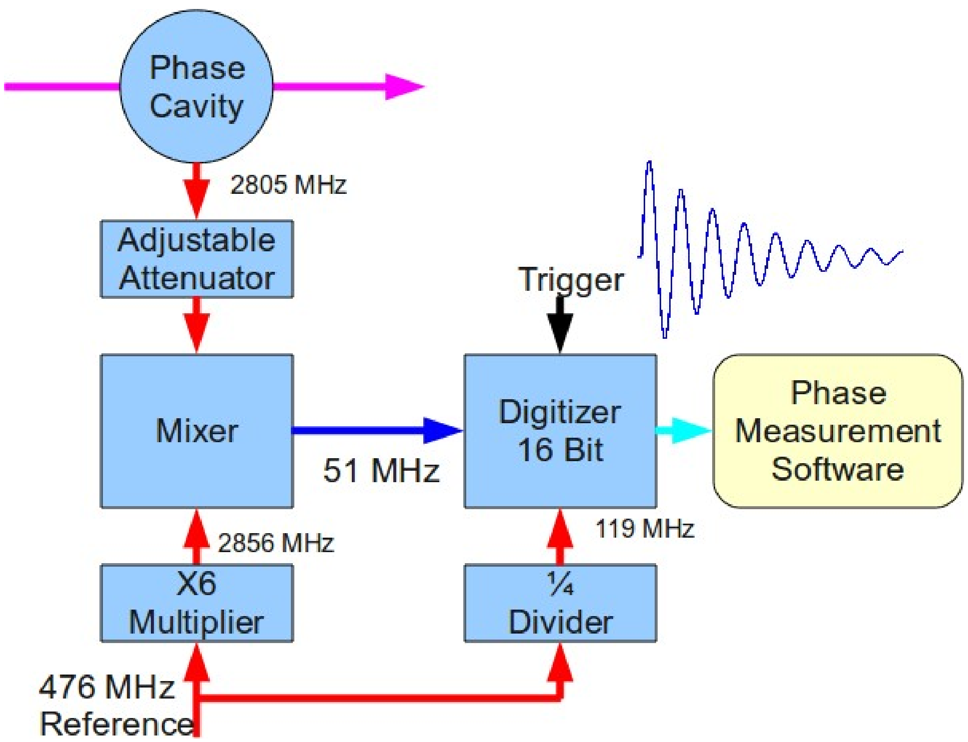
- If cavity decay time >> interpulse spacing you don't integrate the entire signal for each bunch
  - Beam train average position resolution improves with higher Q, but single bunch noise and linearity start to degrade
- If cavity decay time << interpulse spacing (to allow independent measurements without math) the peak signals are higher and linearity suffers
- Adding damping (as opposed to increasing coupling) throws away signal – in most cases not a good solution.
- Ideal is probably for decay time ~interpulse spacing, but detailed study is required
- Multi bunch cavity BPMs for LCLS_II (8.4ns spacing) may be challenging.

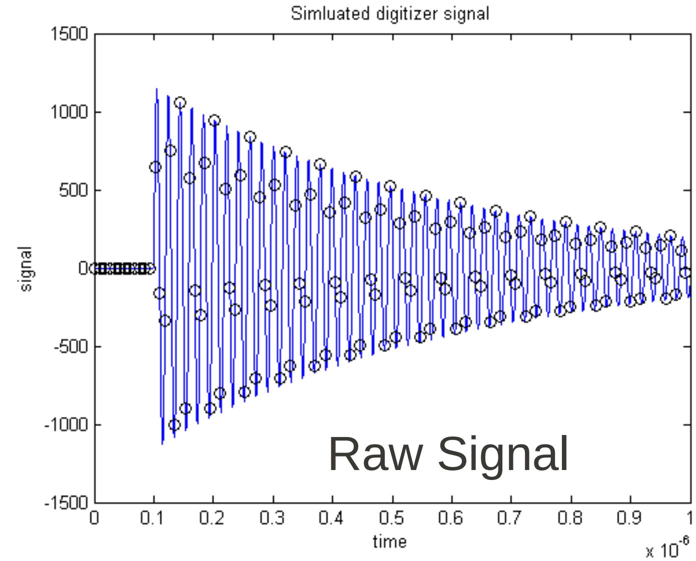
Beam arrival time cavity (LCLS)

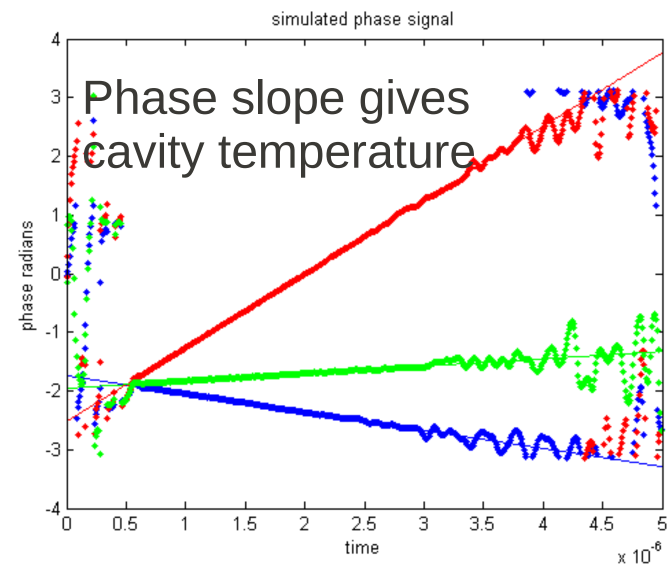
Similar to a cavity BPM but use the monopole mode

Phase drift from cavity temperature is the most significant problem

1us time constant, 10^{-5} /C° temperature coefficient -> 10ps/C° (!)



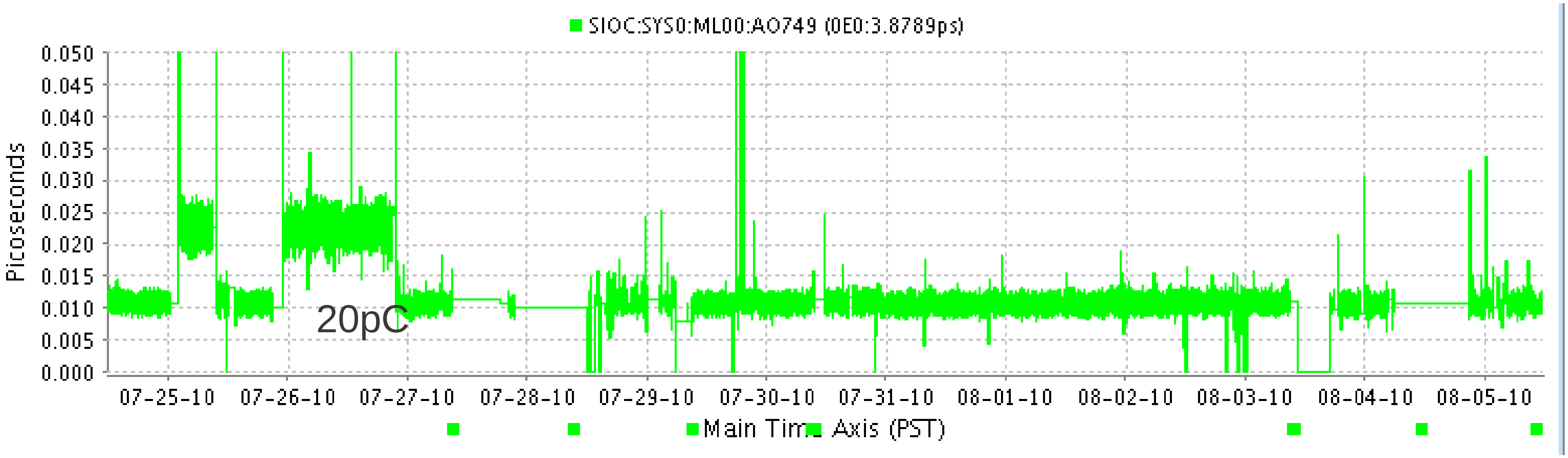




Beam Arrival Time Cavity - Noise

Compare 2 independant cavity systems to estimate noise

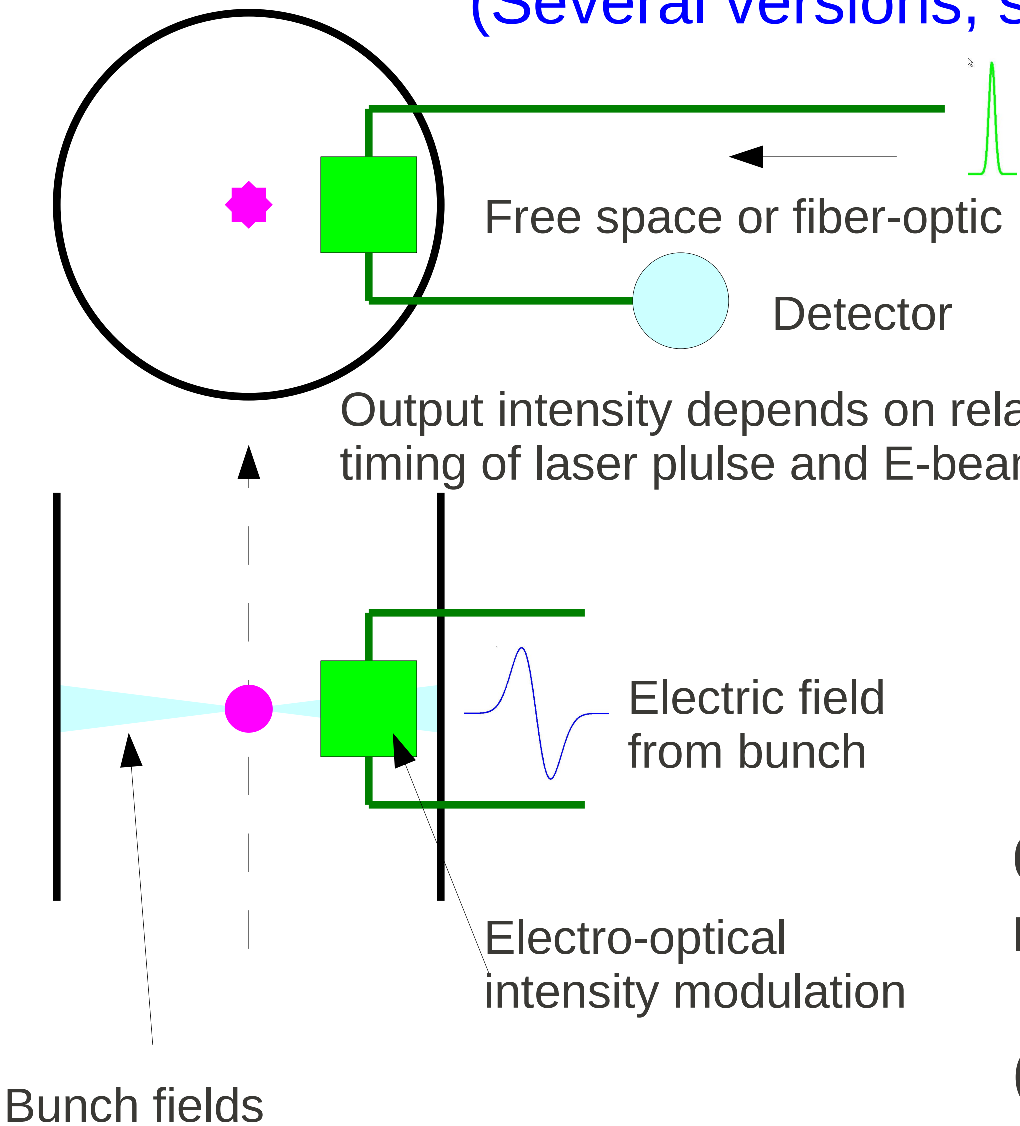
Present system designed for 250pC, needs more gain to operate properly at low charge



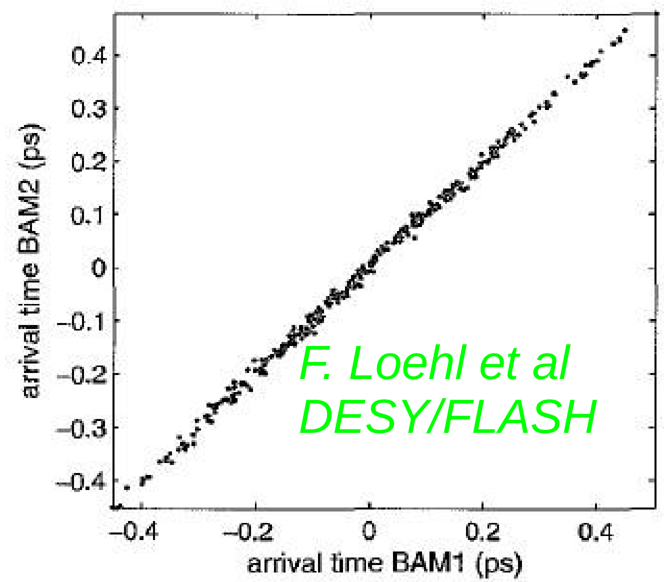
RMS difference between cavities ~12 femtoseconds RMS at 250pC, 25 femtoseconds at 20pC
Drift is ~100 femtoseconds p-p over 1 day.

EO Beam Time Measurement

(Several versions, simplified concept shown)



Output intensity depends on relative timing of laser plulse and E-beam



6 femtosecond timing noise published

(Believe ~3 fs achieved)

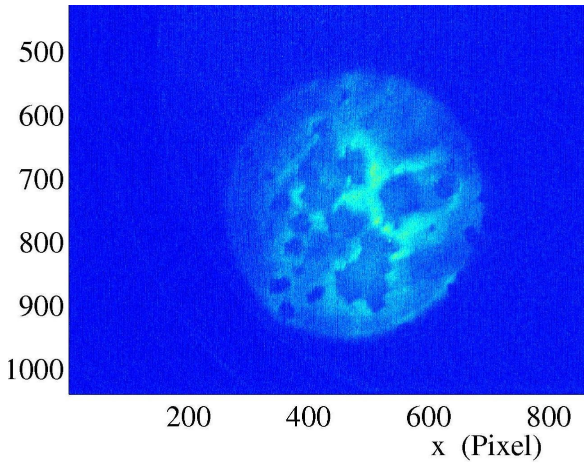
E-Beam Profile Monitors – YAG

Low energy beams (6 MeV) in LCLS
135 MeV in the injector spectrometer
Main dump spectrometer

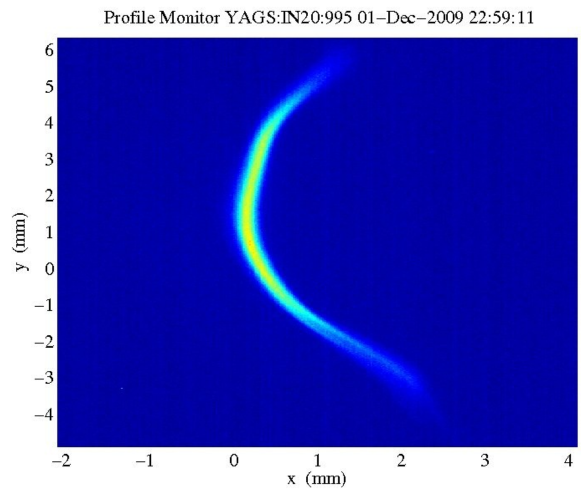
High brightness, but saturates for high intensities

Saturation at 0.04pC/um^2 measured
250pC in 50um spot is 2X this density.

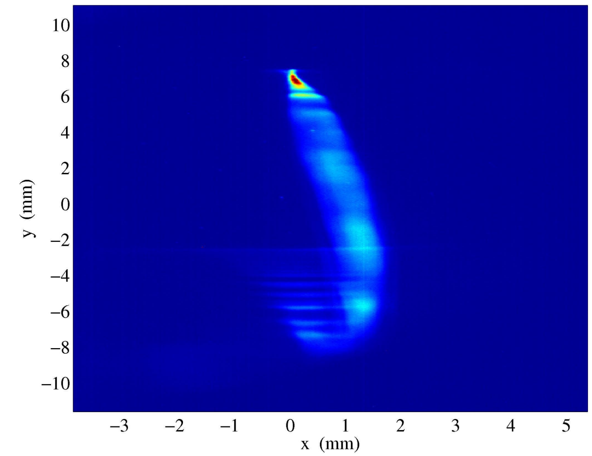
A. Murokh et al PAC2001



Solenoid adjusted to give an electron emission image of the photocathode (6 MeV)



135 MeV spectrometer with TCAV on.

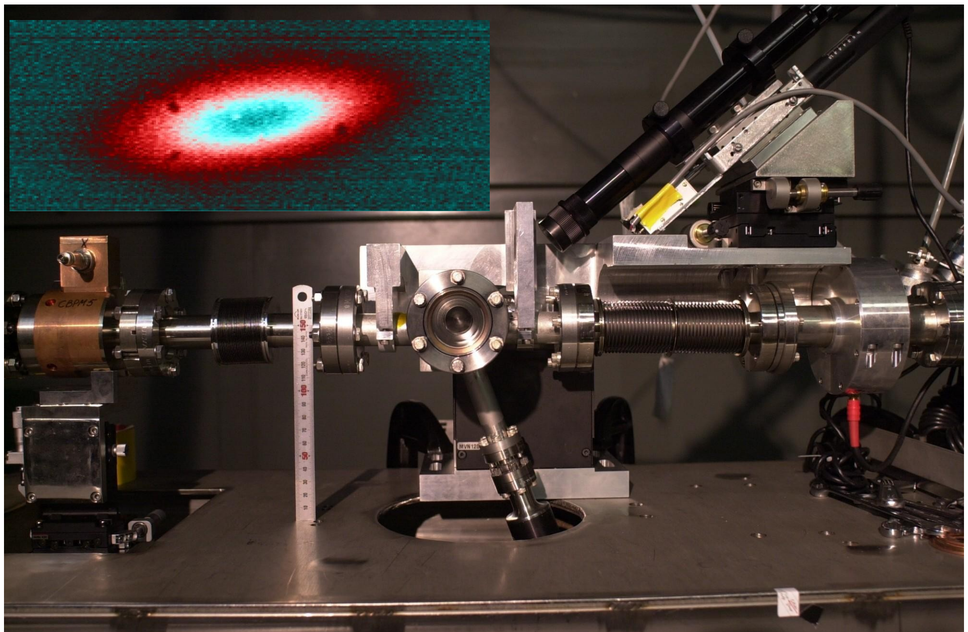


Main dump, 4.5 GeV, over compression, laser heater off, showing microbunching instability

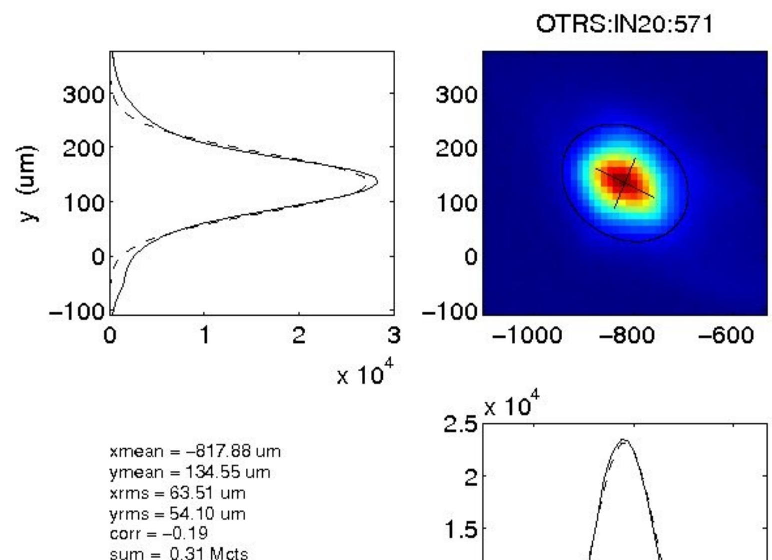
Fluorescent screens generally not usable for high energy high brightness beams

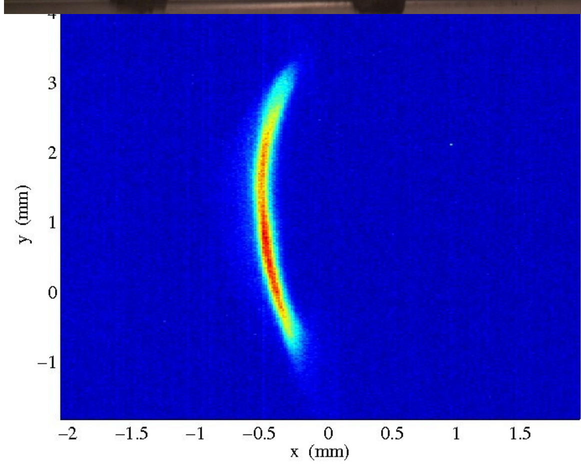
E-beam Profile Monitors: OTR

OTR emission is linear and can provide high resolution



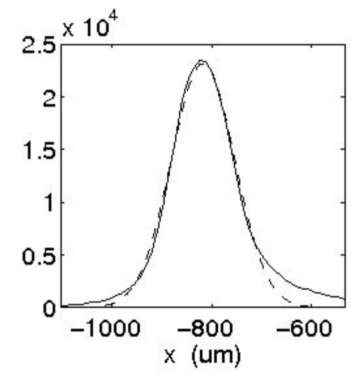
OTR spot size monitor at ATF2 Measured 5um RMS spot. (calculated resolution 2um RMS)





OTR image of streaked beam at 135 Mev at LCLS

135 MeV Spot

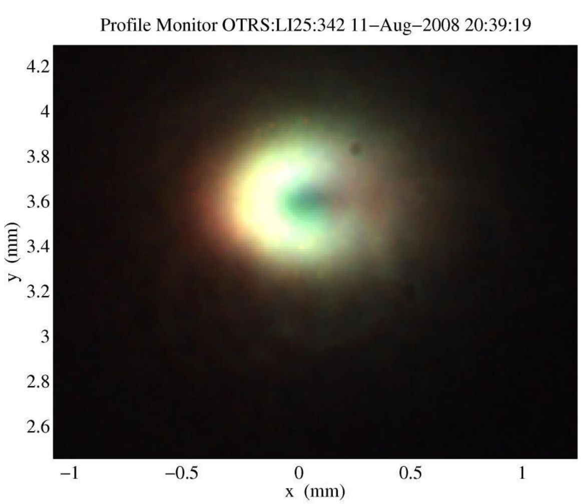


COTR

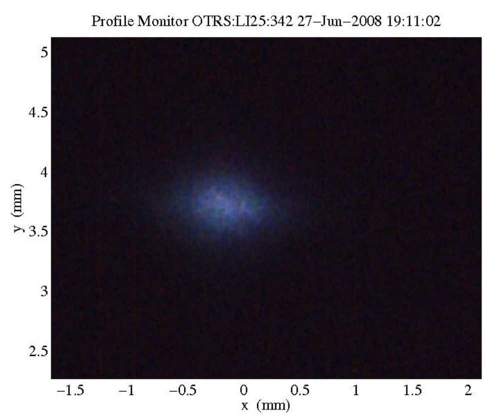
Beam contains longitudinal structure at optical wavelengths. Coherent emission from this modulation dominates the OTR output and prevents measurements.

Cannot use OTRs at LCLS after first bunch compressor.

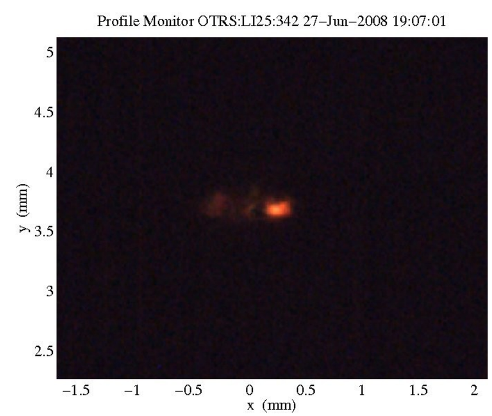
COTR also observed at DESY/FLASH, BNL, SLAC/NLCTA , Fermi/ELETTRA



True color image



Incoherent image (foil used to ruin emittance)

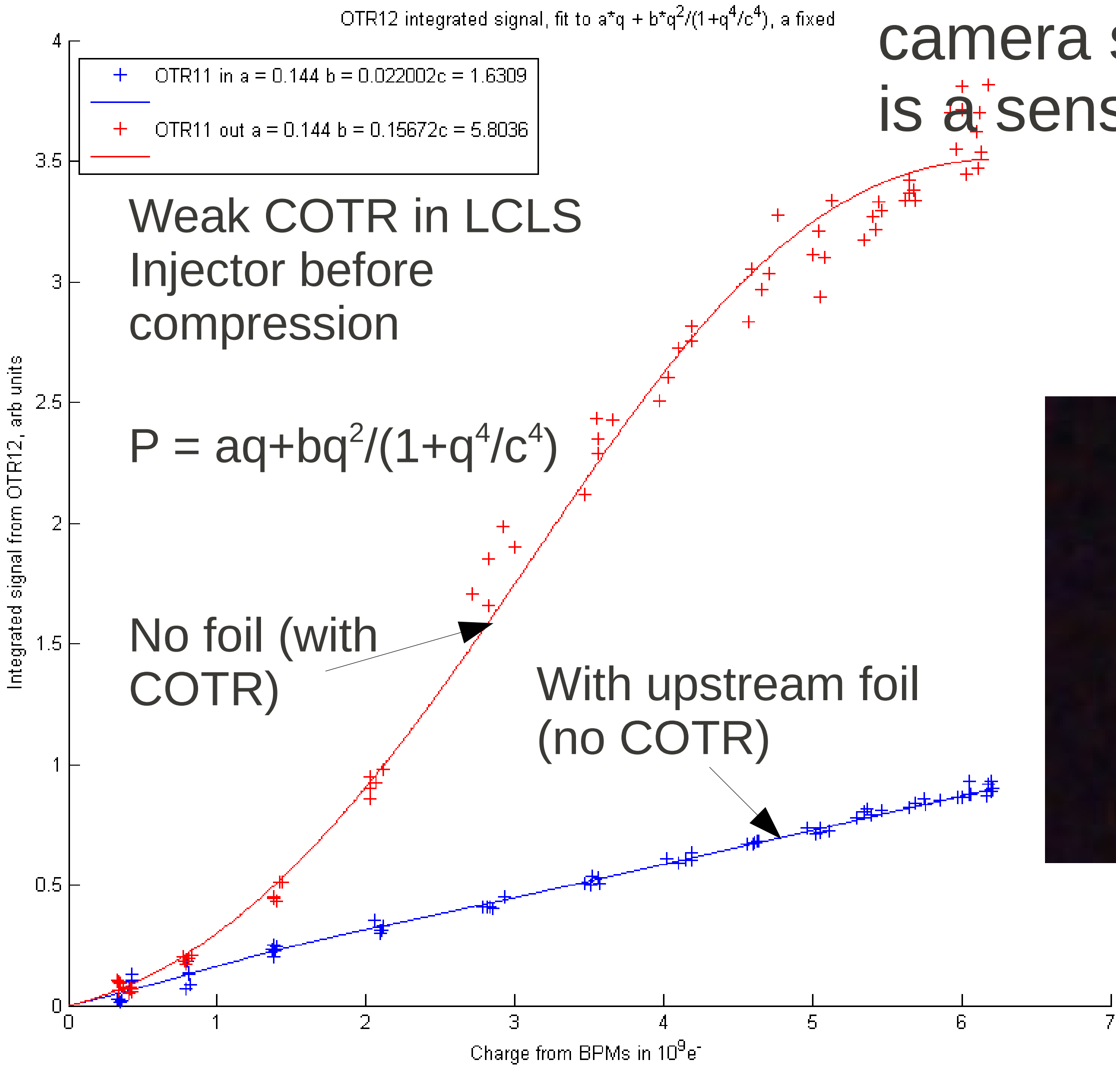


Coherent image X100,000 optical attenuation!

Detecting COTR

Nonlinearity of integrated camera signal vs beam charge is a sensitive measure of COTR

Integrated camera signal



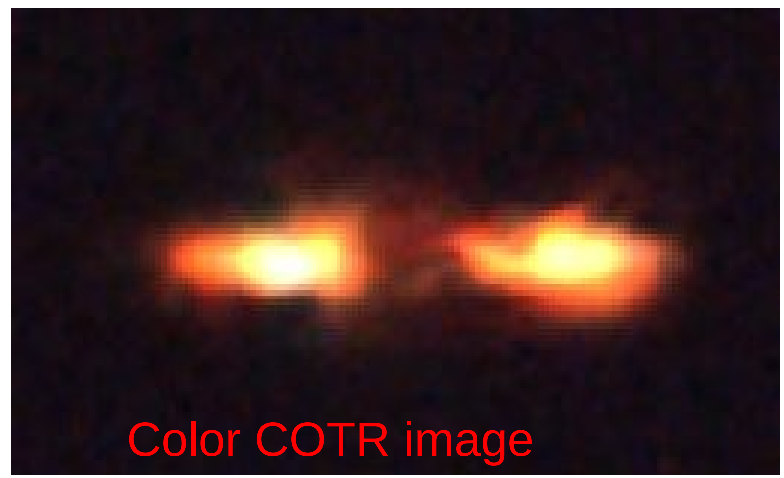
Weak COTR in LCLS Injector before compression

$P = aq + bq^2/(1+q^4/c^4)$

No foil (with COTR)

With upstream foil (no COTR)

Electron beam charge



Sometimes COTR just stares you in the face!

Can We Fix COTR?

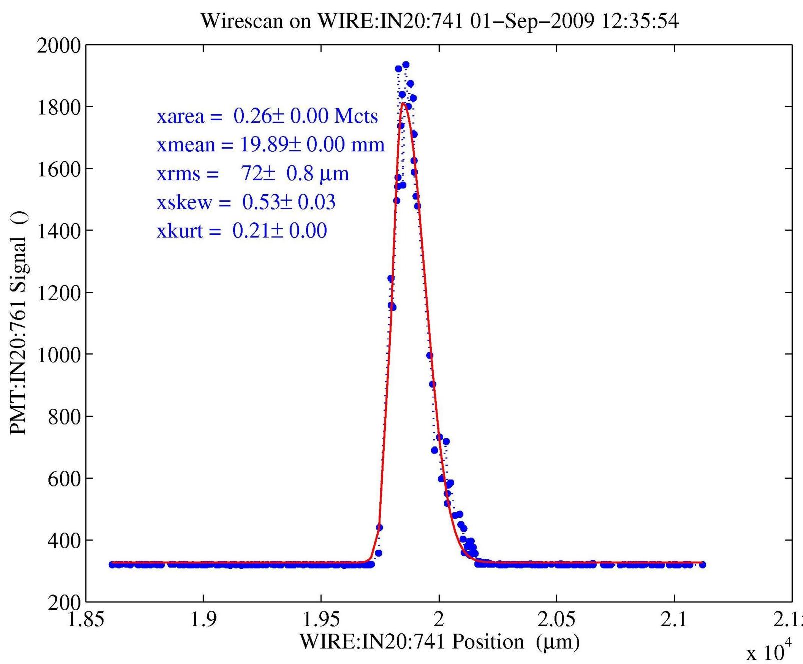
- COTR is NOT a mystery: simulations are in reasonable agreement with observed COTR enhancement at LCLS
  - The simulations assume only shot noise – no reason to believe this is related to the type of source laser used.
- Laser heaters help – but not enough
- If beam were fully coherent, maybe we could use the COTR, but with partial coherence it is difficult.

My Opinion: I think OTR screens will continue to be unusable on high brightness high energy accelerators – but I am happy to be proven wrong!

Wire Scanners

Move a wire through the beam, measure degraded electrons or gammas downstream.

Note: measuring secondary emission usually doesn't work well: space-charge limit on the wire causes non-linearity for short FEL type pulses.

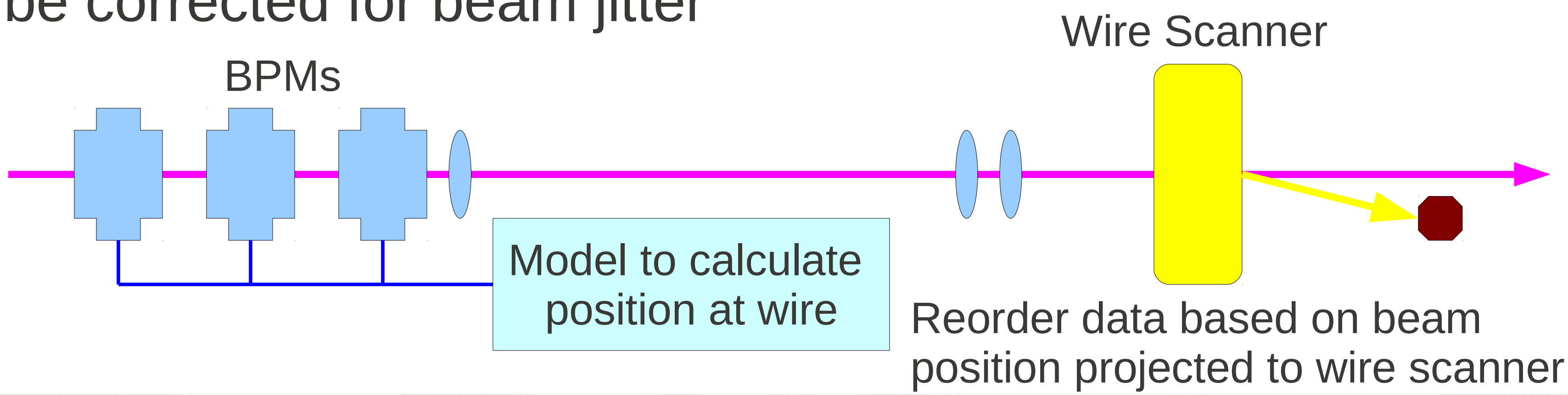


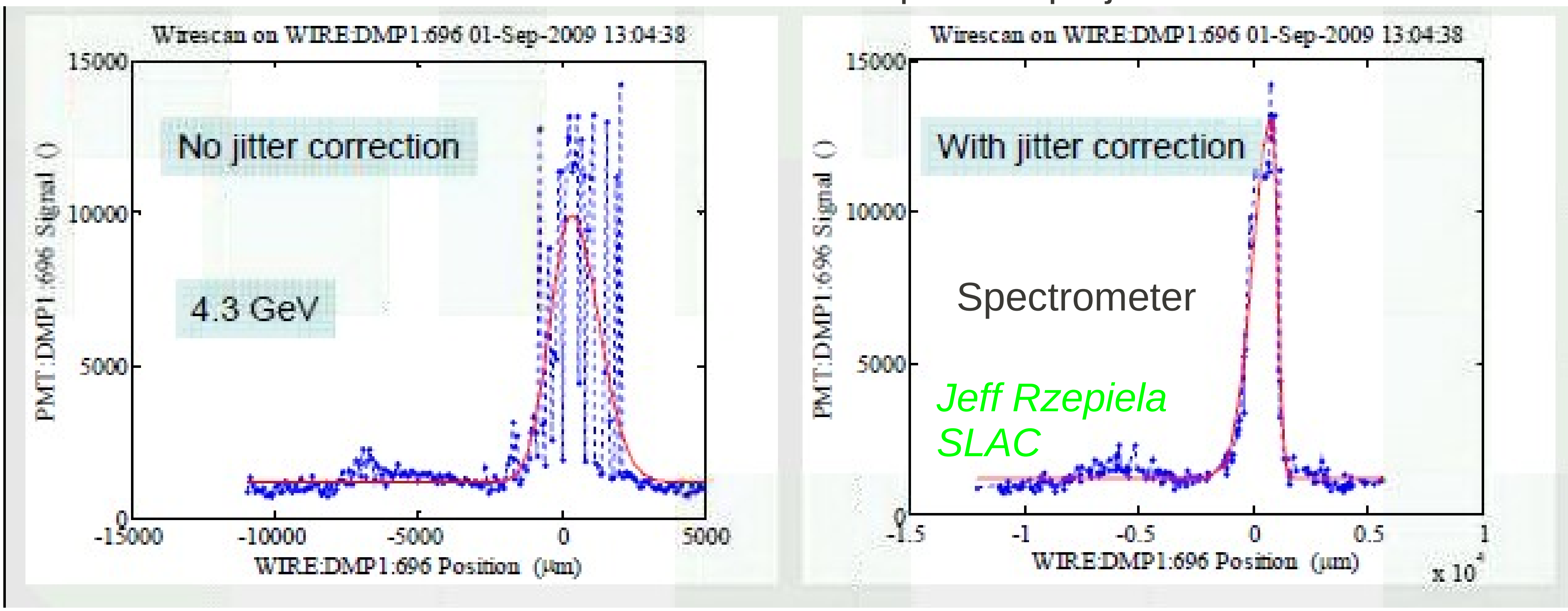
Wire scans only provide 1-d integrated, mult-shot beam profiles but they are the only method we have found that work with the LCLS beam .

Wire scan in LCLS injector, 72um RMS beam size

Jitter Correction for Wire Scanners

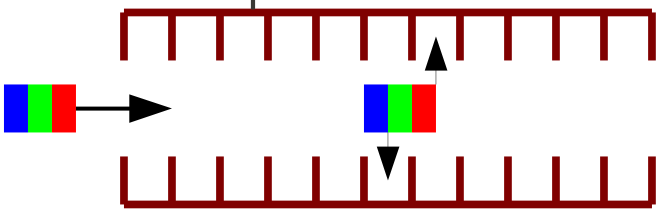
Wire scanner measurements are multi-shot so signal must be corrected for beam jitter





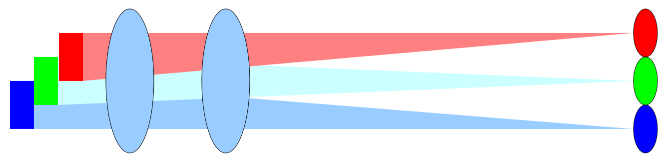
TCAV Bunch Length Measurement

Transverse cavity provides time dependant kick



Optics for 90 degree phase advance

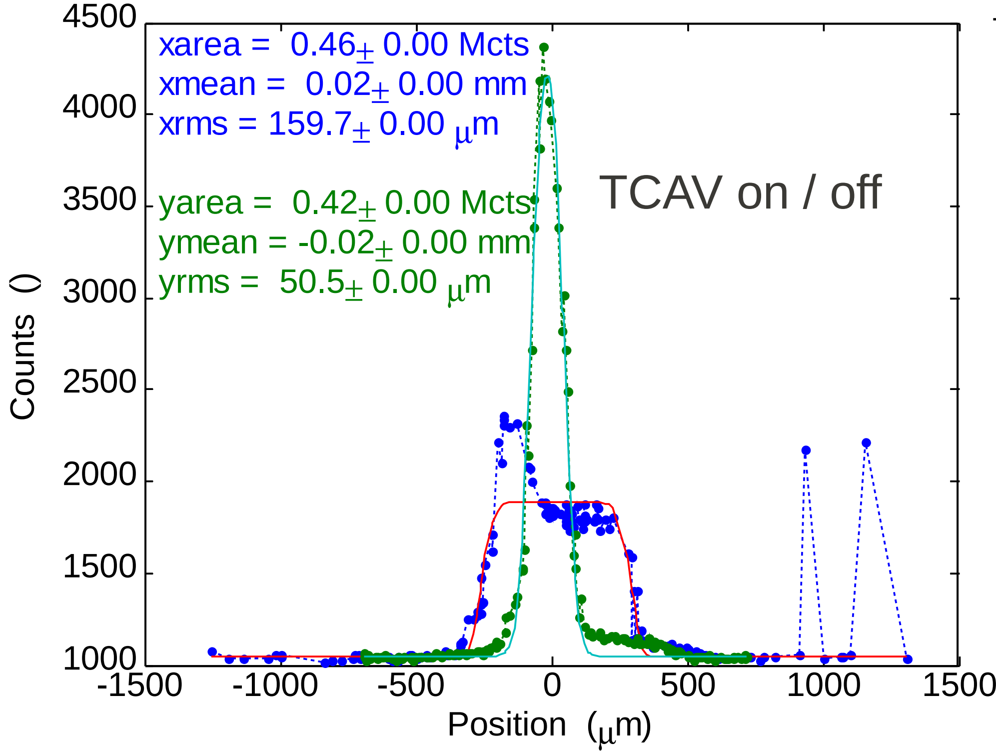
Profile monitor

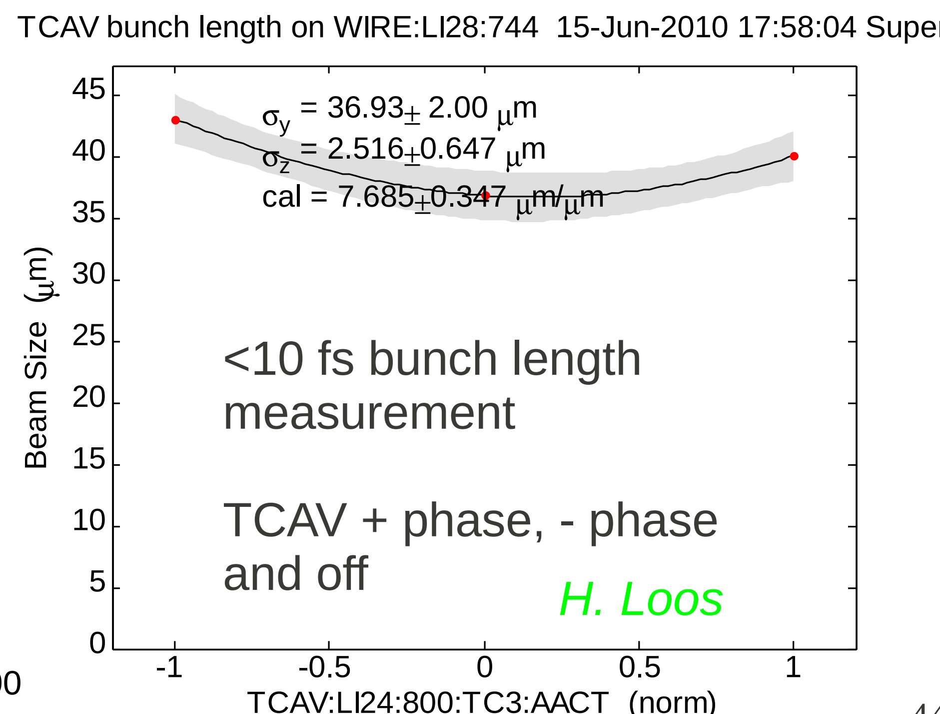


Longitudinal transformed to transverse

15MV 2856MHz at LCLS

LCLS uses a wire scanner to measure the profile

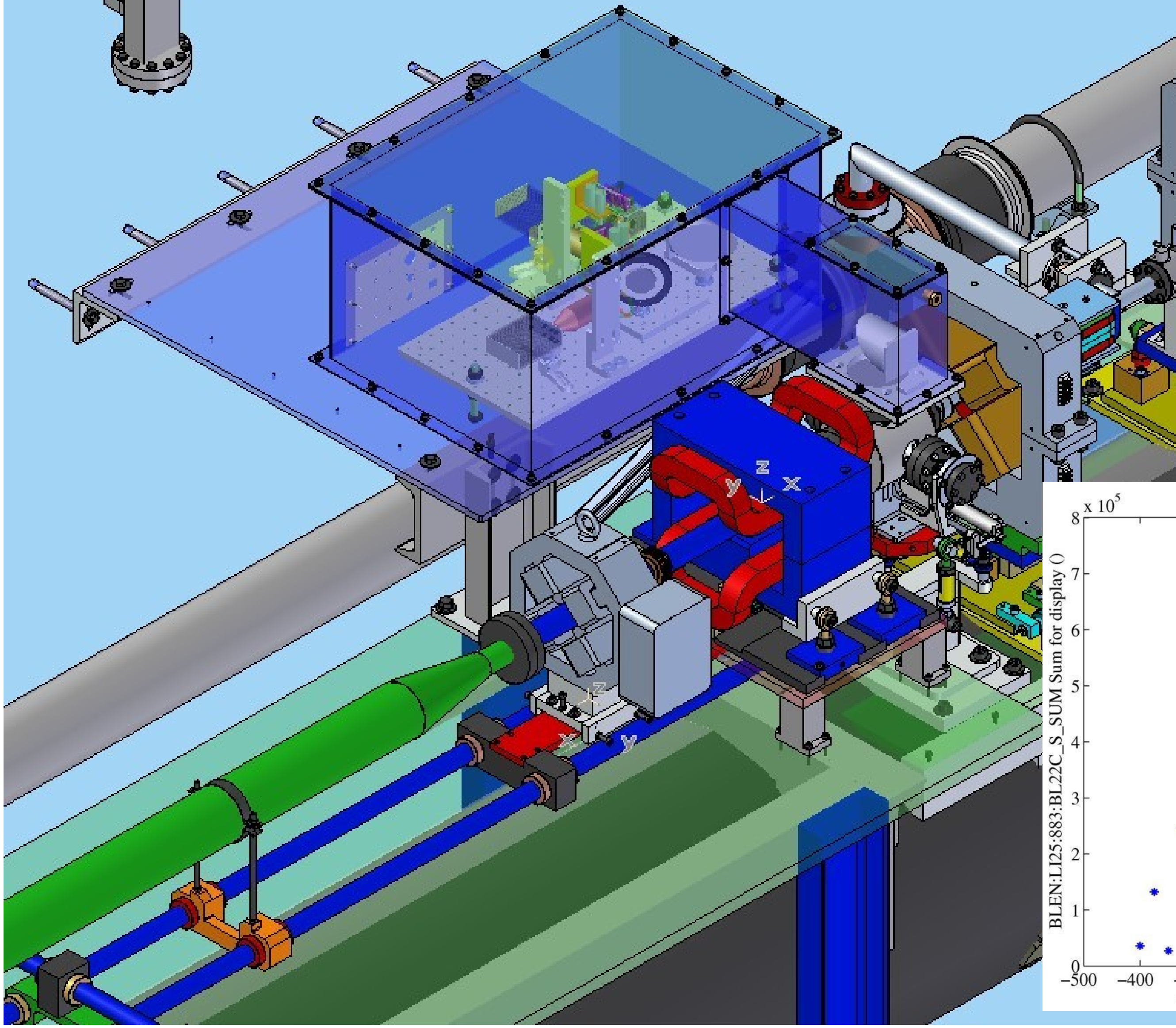




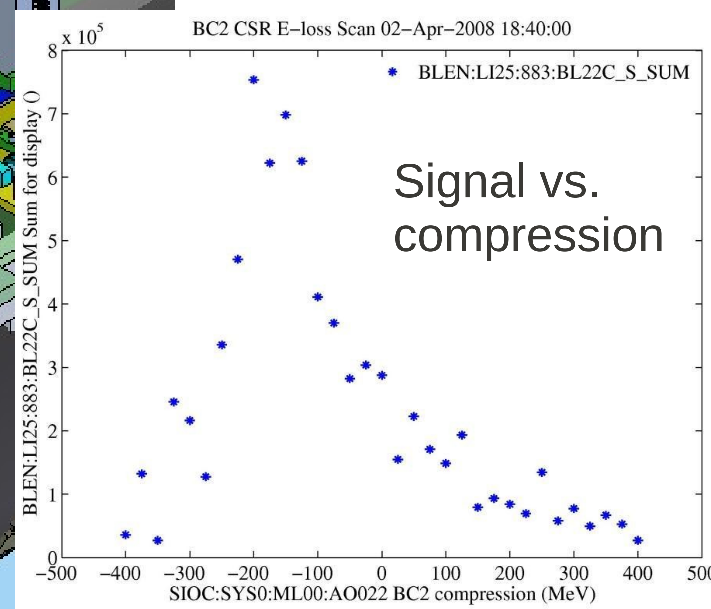
Transverse Cavity Resolution

- Resolution of transverse profile measurement is usually not a limit
- Transverse kick relative to uncorrelated transverse energy spread is a limit
  - Ideally would use large beta to match beam size to TCAV aperture – but may not be practical in many cases
- Higher deflection power and higher frequency improve resolution
  - 40 MV X-band deflector under development at SLAC
- Few-femtosecond resolution looks practical

Relative Bunch Length Monitor

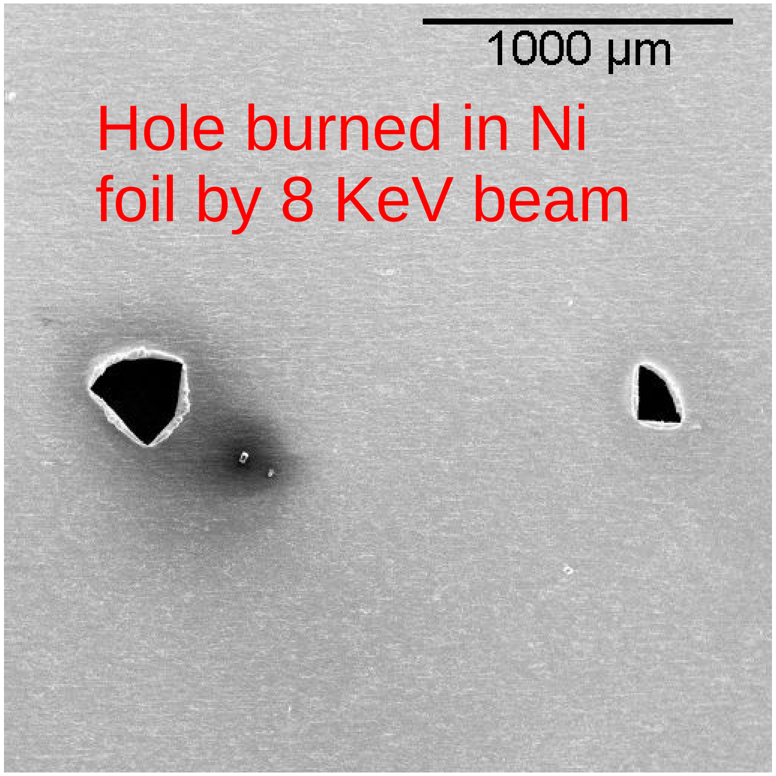


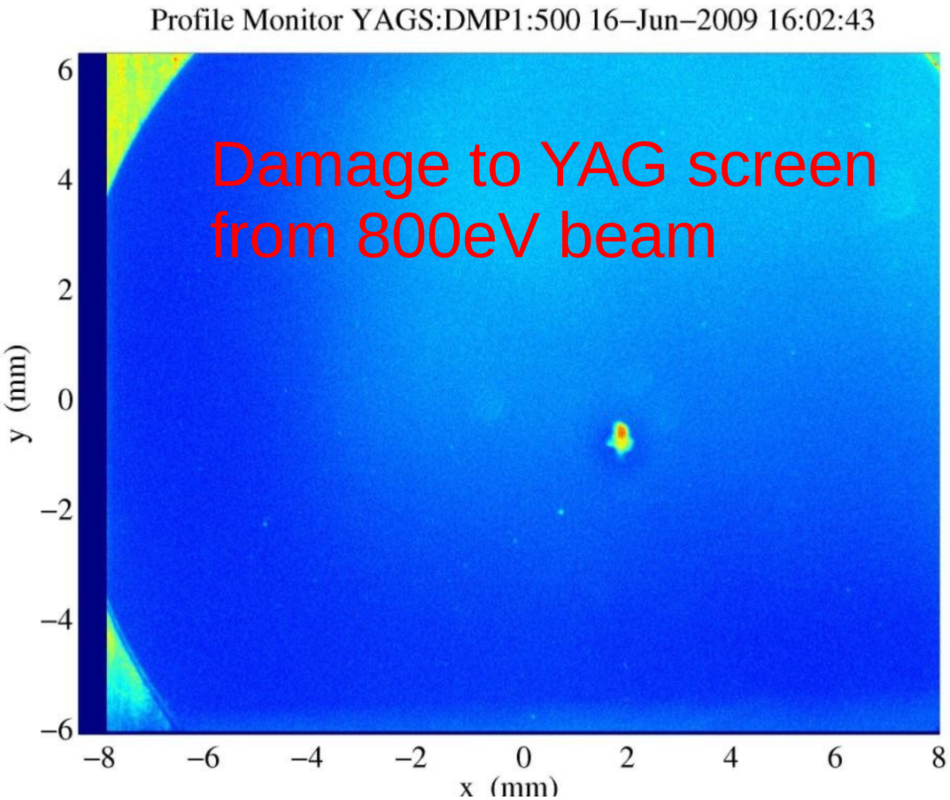
Pyroelectric detector good from 100GHz to light



X-ray FEL Measurements

High pulse energy density from XFELs is a significant diagnostics problem – will damage most materials and saturate detectors.

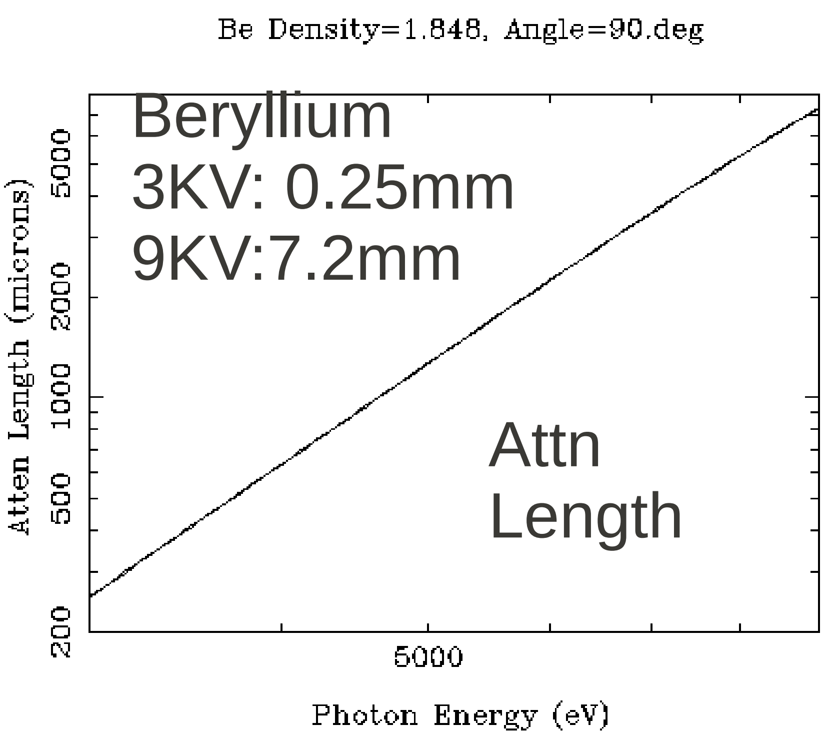


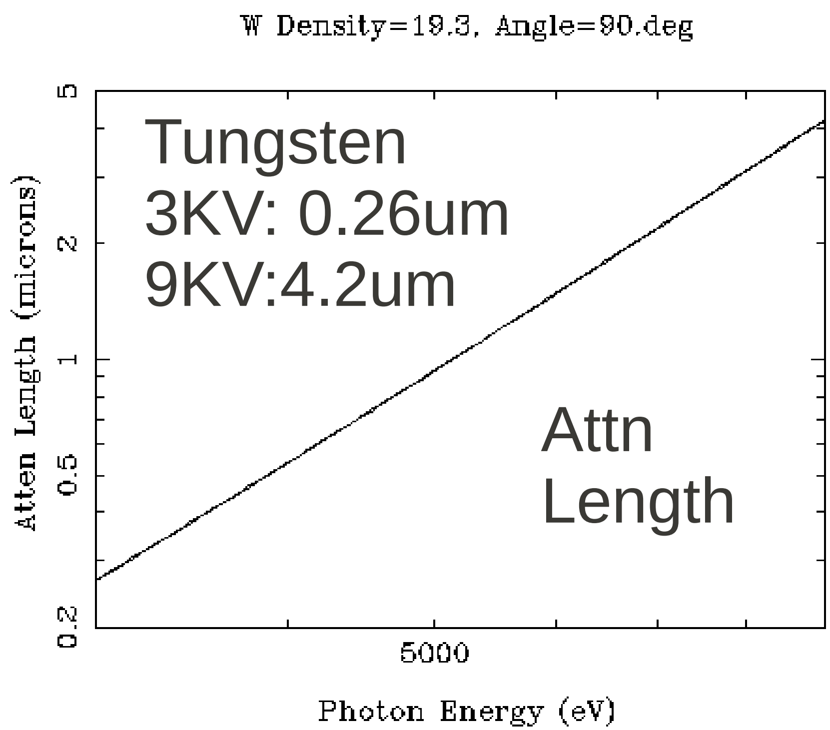


Attenuating X-ray beams

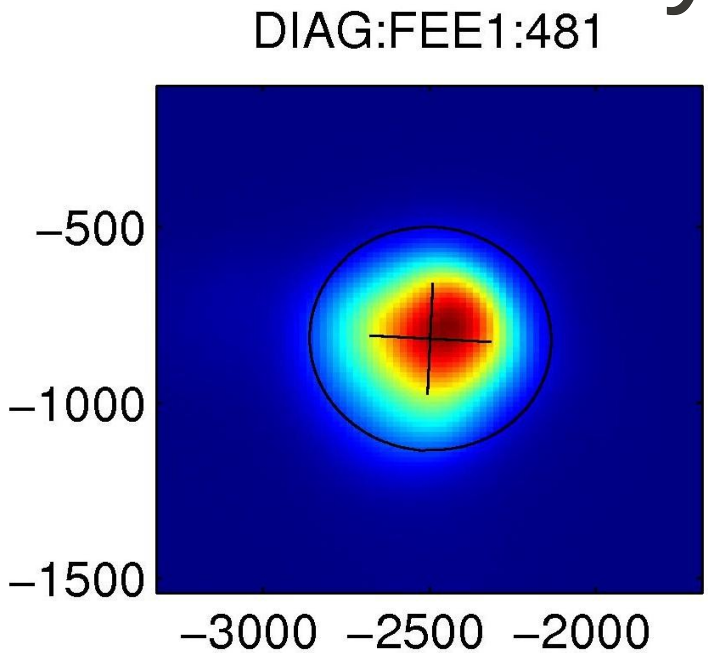
3rd harmonic transmission always higher than fundamental transmission

FEL contains ~1% 3rd harmonic.
At large attenuation 3rd harmonic light will dominate measurements

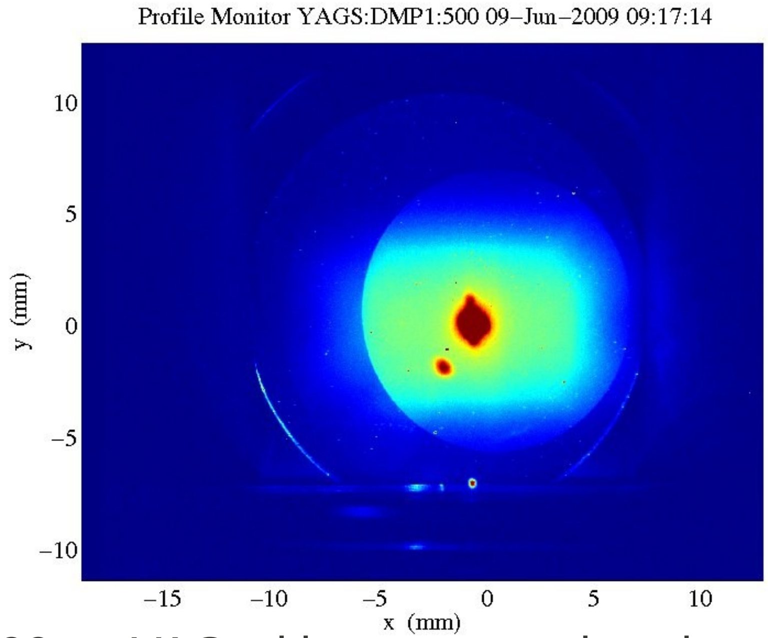




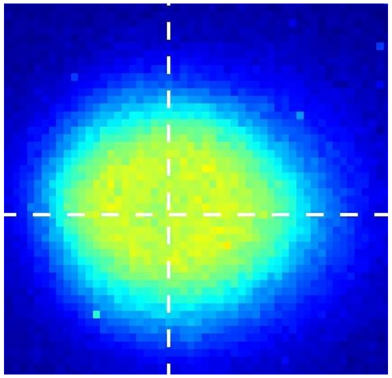
X-ray YAG Screens



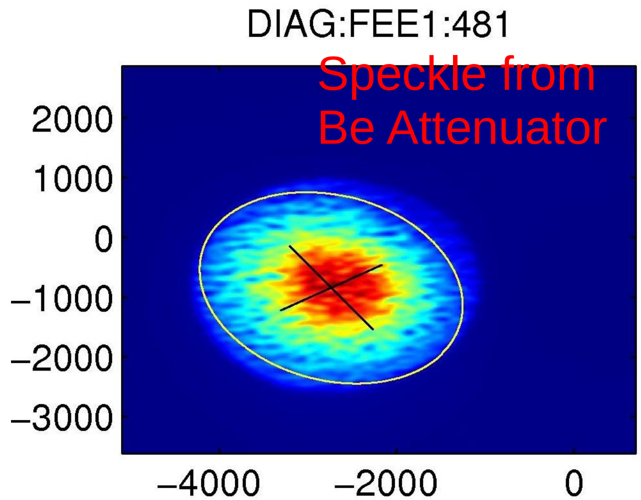
100um YAG, 10 KeV Beam



100um YAG without attenuation showing spontaneous and saturated FEL spot



YAG screen showing saturation with low energy photons



X-ray Pulse Energy Measurement

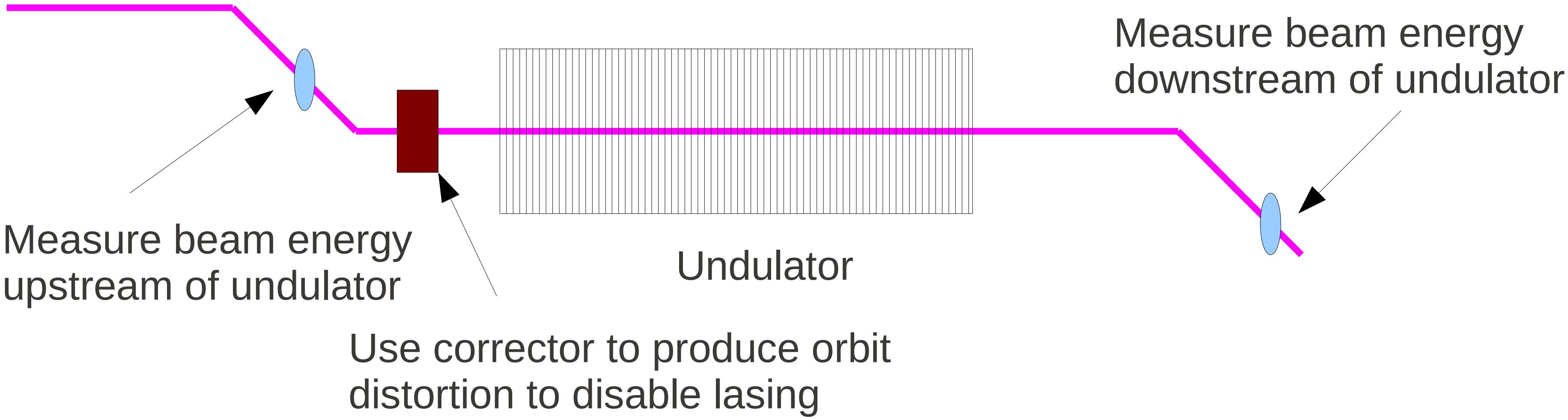
Measurements with conventional detectors or fluorescent screens are difficult due to high beam intensity

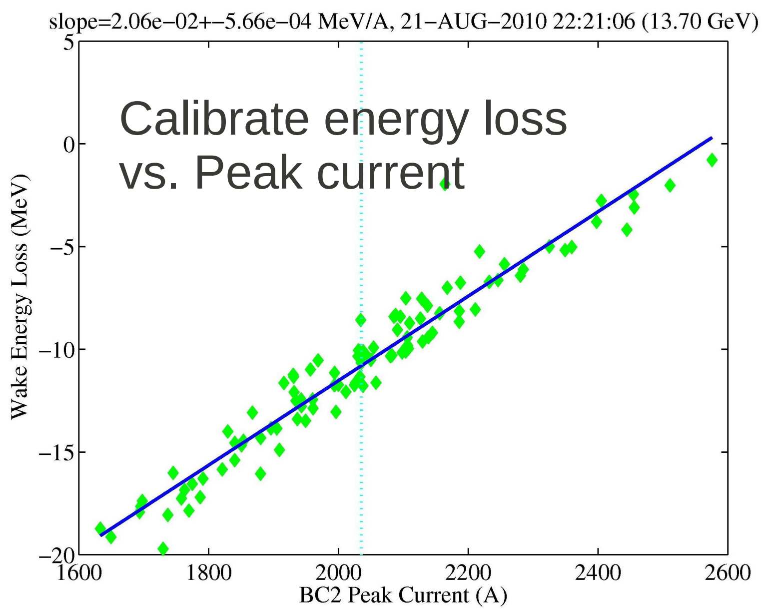
Calorometric detectors can provide calibrated average power measurements

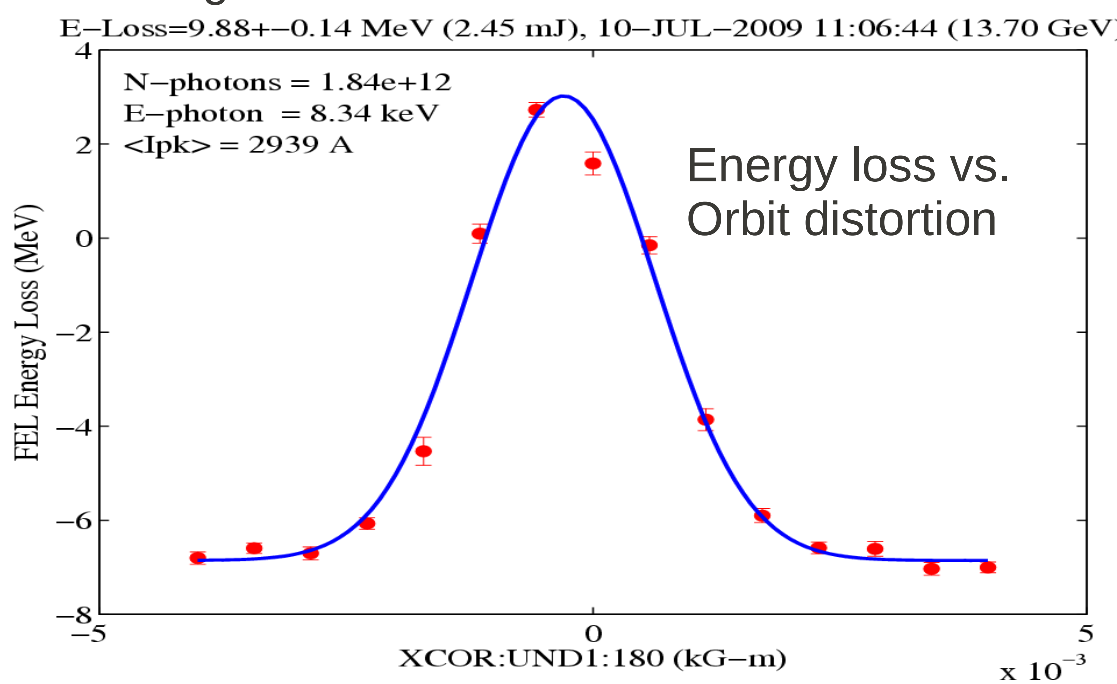
Electron beam energy loss measurement used at LCLS for calibrated pulse energy measurements. Energy loss from wakefields contributes significantly to noise, but can be removed by calibrating against peak current variation

Gas detectors used at LCLS for pulse to pulse measurements.

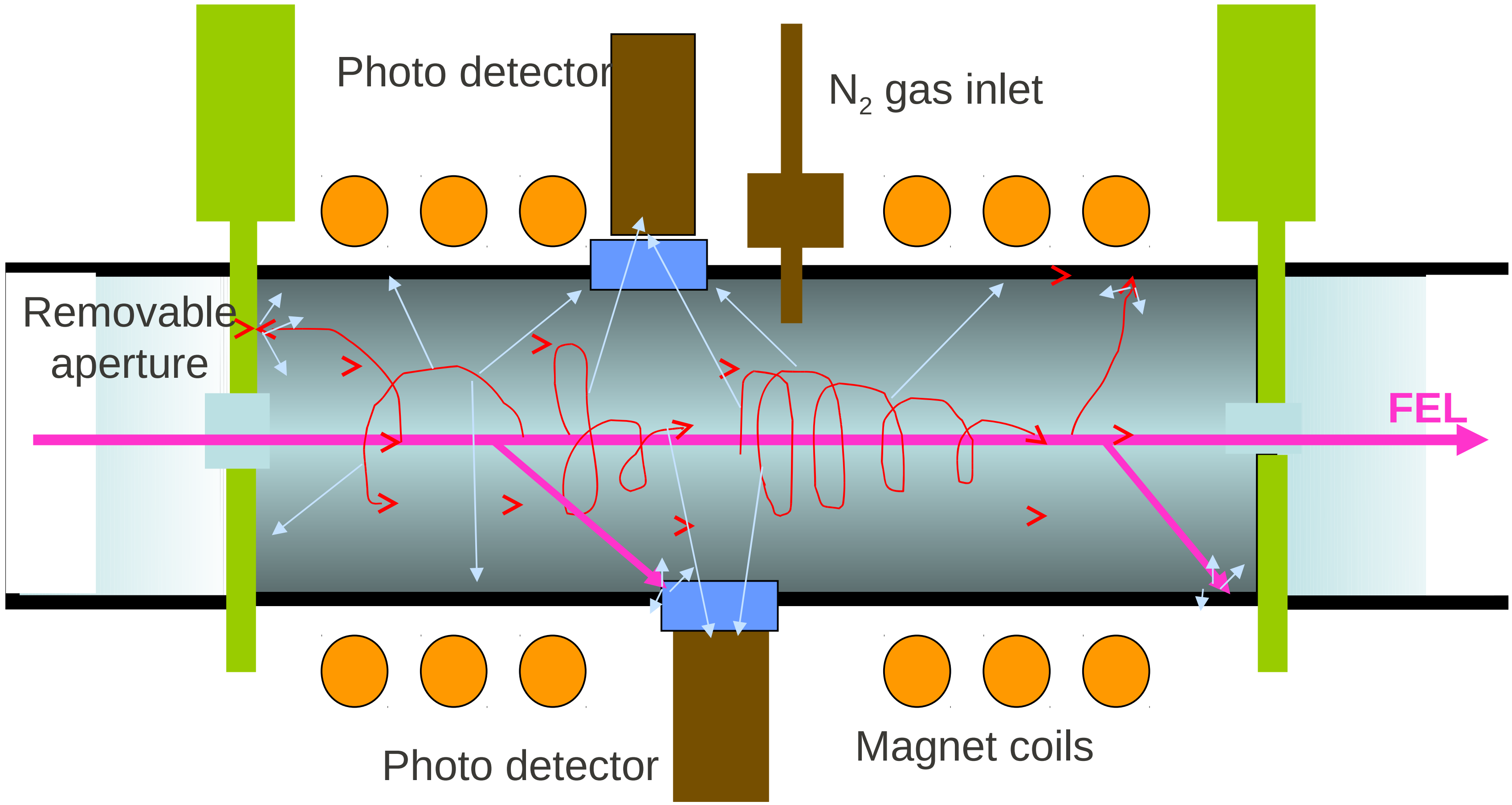
E-beam Energy Loss Measurement







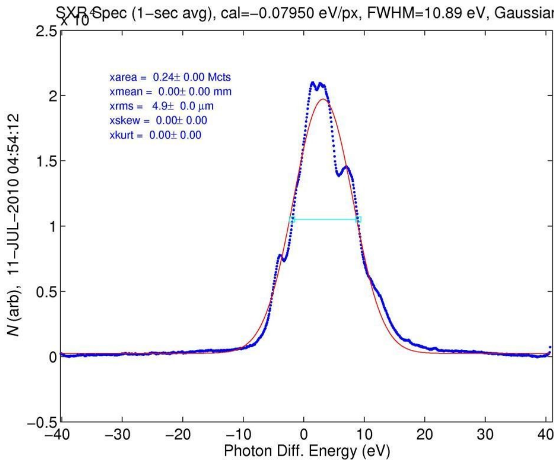
Gas Detector

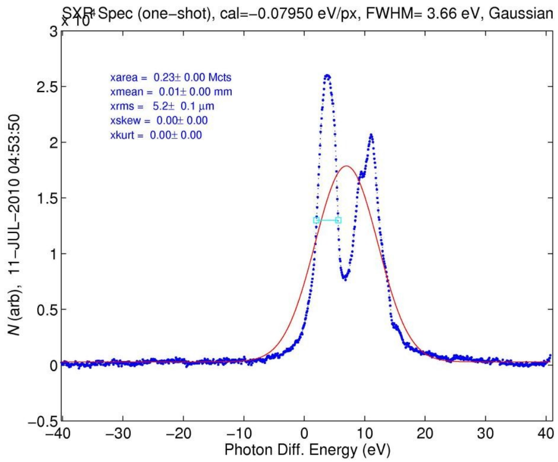


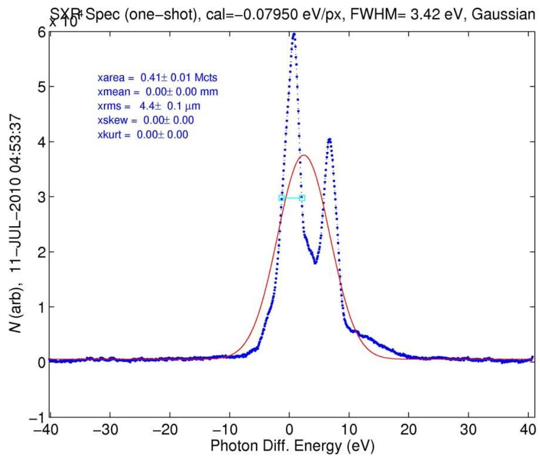
Primary photoelectrons cause N_2 molecules to fluoresce in the near UV

Vital for user operations: Provides non-invasive shot by shot pulse energy to users and accelerator operations

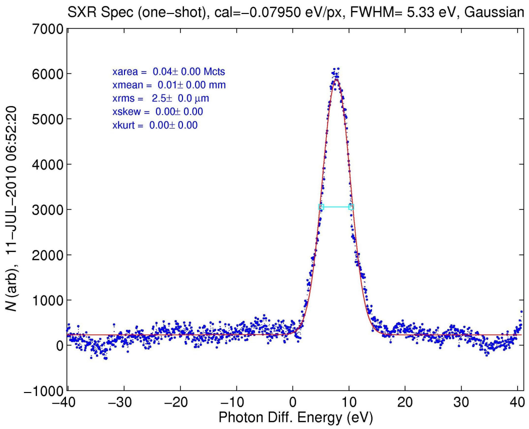
X-ray Grating Spectrometer

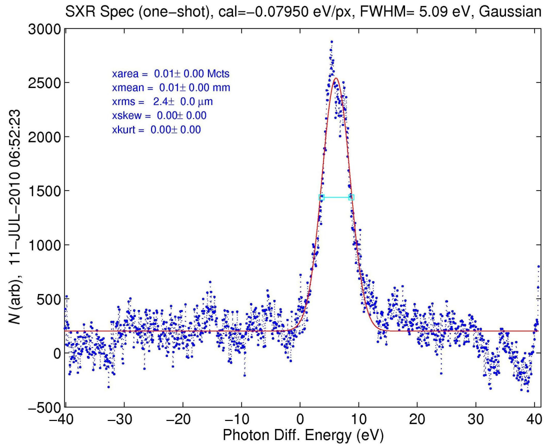


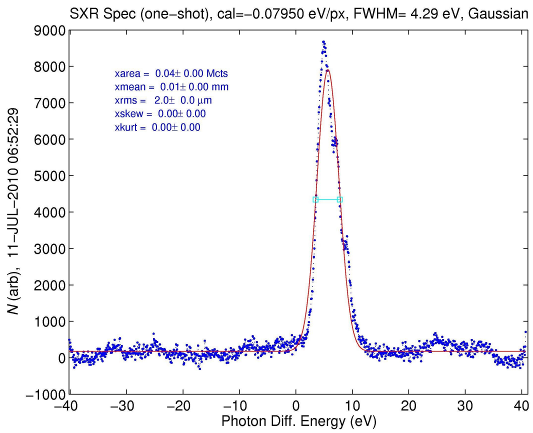




3 Spectra taken at 20pC, normal operation, few spikes visible







Spectra taken with 20pc, slotted foil in: maybe 1 spike.
Simulations suggest 1-2 fs FWHM in this condition

Diagnostics problems

- Transverse profile measurements for high brightness beams
- X-ray pulse temporal measurements
  - Several ideas, but most look more like experiments that diagnostics
  - Ultra short X-ray bunches will require femtosecond timing for experiments
- Non-invasive X-ray spectral measurements

Important Things **Not** Covered Here

- Wide variety of diagnostics
  - Toroids, beam loss monitors, halo monitors, etc
- Everything after the digitizer
  - Firmware, software, applications
- Accelerator design to enable diagnostics
  - Beamline layout, lattice design, modeling
- Mechanical design
  - No point in a nanometer resolution BPM if the support structure moves by microns