Review of Instrumentation and Feedback for Beam Instabilities

Guenther Rehm

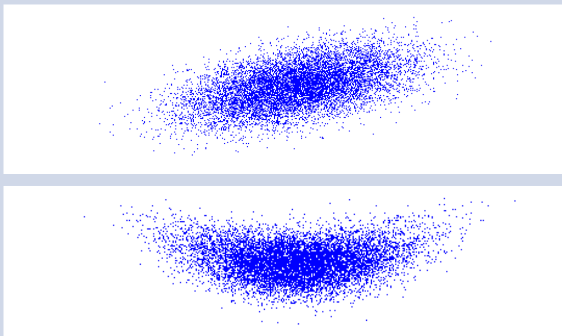
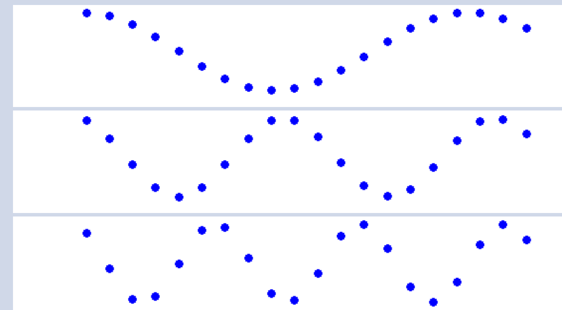
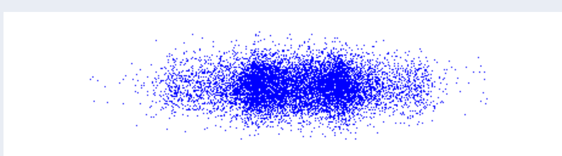
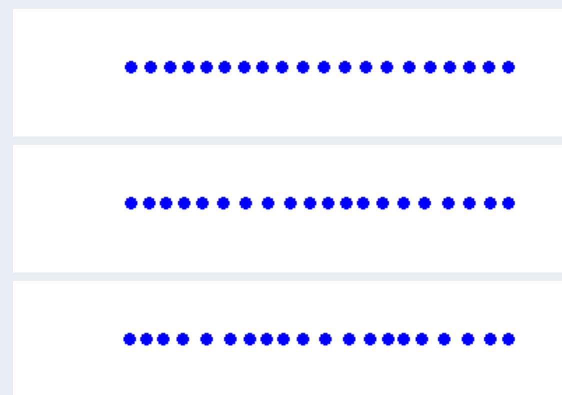
TWIICE workshop, Soleil

16-17 Jan 2014

Overview

- What types of beam instabilities can be observed in storage rings?
- Which Diagnostics can be used directly or indirectly?
- Where are the limits of these Diagnostics?
- What is possible with feedbacks?
- What might become technologically possible in the near future, what would be desirable?

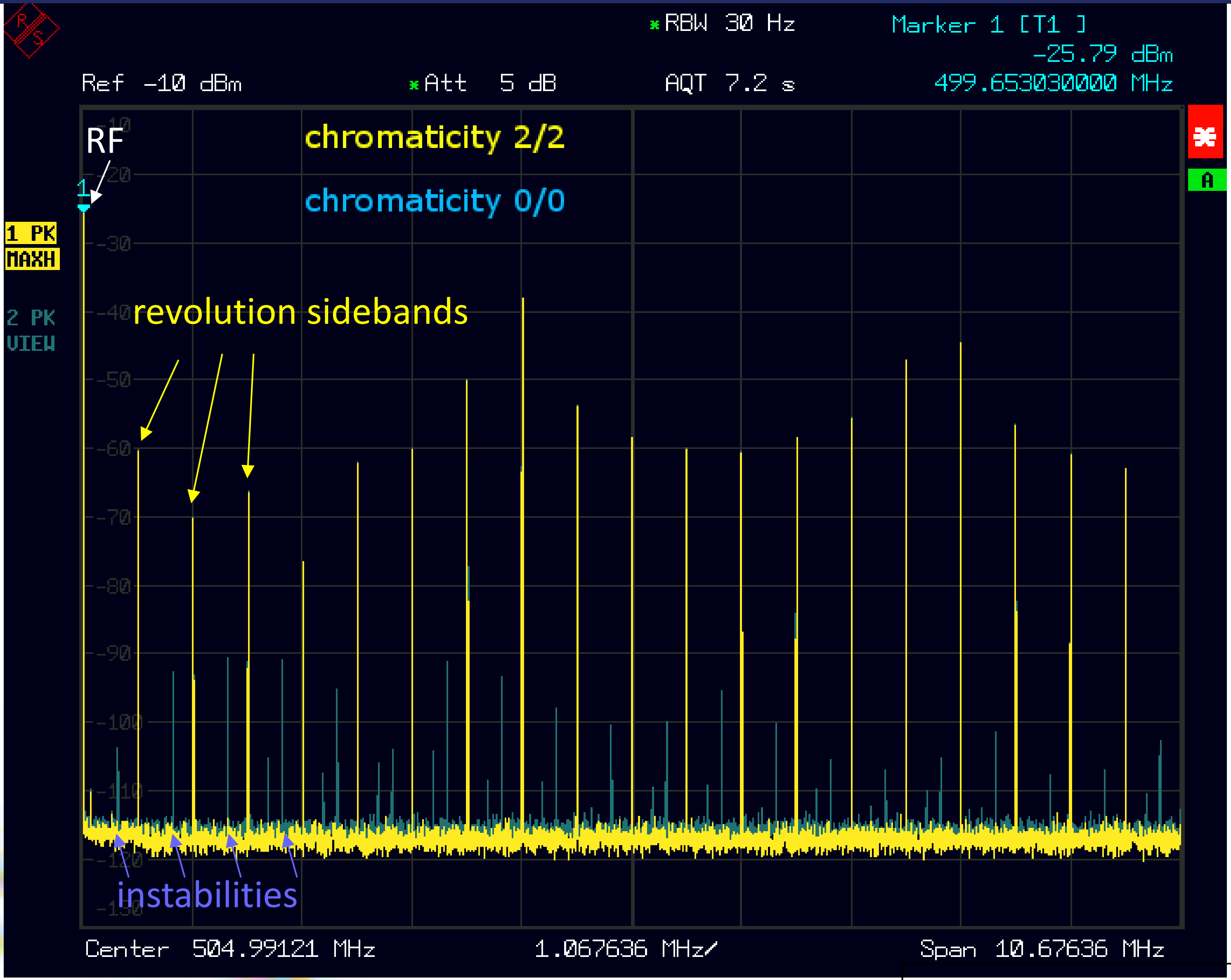
Types of Instabilities

	Single Bunch	Coupled Bunch
Transverse	Strong Head-Tail Instability Transverse Mode Coupling Instability 	Transverse Multibunch Instability Ion Instability 
Longitudinal	Microwave-Instability Longitudinal Mode Coupling Instability Micro-bunching 	Longitudinal Multibunch Instability 

Spectrum Analyser on BPM

- Idea: Instabilities have characteristic frequencies!
- A single diagonally offset BPM button will pick up a rich spectrum composed of:
  - RF frequency and harmonics, decreasing in amplitude with Fourier transform of bunch profile
  - Sidebands of revolution frequency with Fourier transform of fill pattern
  - Sidebands of both betatron frequencies if transverse instabilities
  - Sidebands of synchrotron frequency if longitudinal instabilities
- A spectrum analyser allows to look at all this over the whole bandwidth of the pickup (5-10GHz typically), with as fine detail as desired, <u>but not full bandwidth and resolution at the same time!</u>

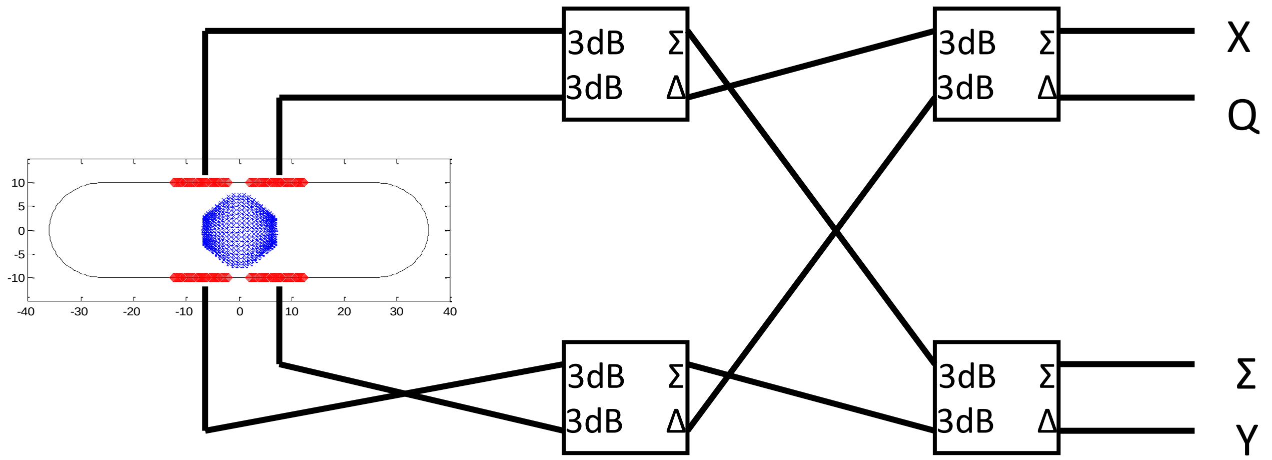
Spectrum Analyser Example



Measurements at Diamond

Spectrum Analyser Limitations

- Dynamic Range: Signal on RF harmonics can be a billion times more powerful than instabilities
  - For transverse observation use 4 buttons and hybrids to suppress monopole signal and look at dipole signal only



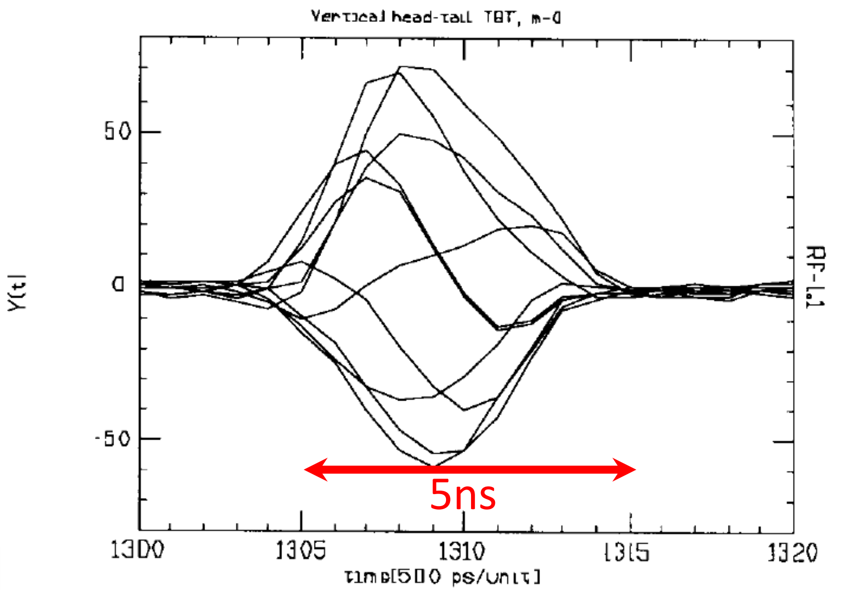
  - For longitudinal observation demodulate with out of phase signal of RF harmonic (requires phase lock to machine RF)
- Swept SA only measures one frequency (within resolution bandwidth) at any time
- ‘Real Time’ SA only measures limited bandwidth (a few MHz) at any time, then FFT

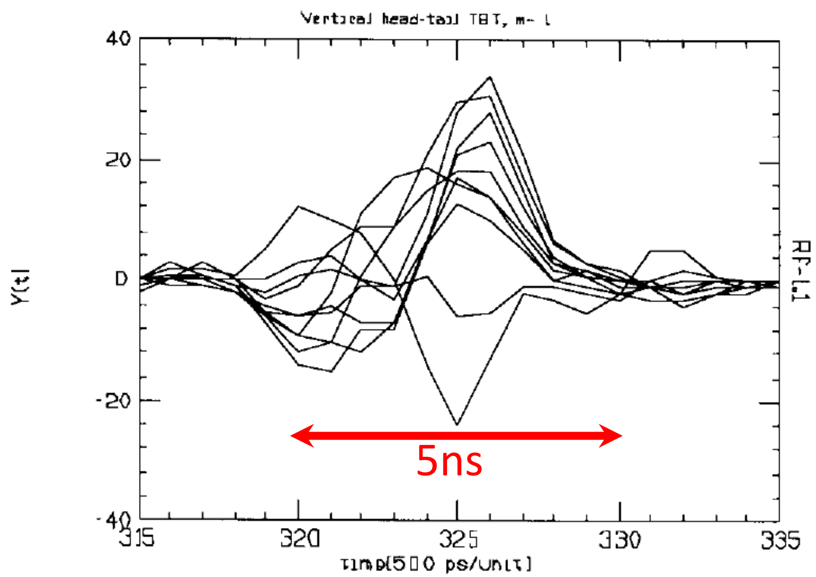
Oscilloscope on BPM

- Bandwidth of modern high speed real time sampling oscilloscopes can easily be as large as bandwidth of BPM pickup
- High sampling rates (10s of GS) mean short (a few ms) timescales can be recorded while producing large amounts of data per observation
- This means full bandwidth (many GHz) can be observed with a few 100Hz resolution!
- Coupled bunch motion can be observed in all detail
- If bunches are long (ns timescales) intra bunch motion can be observed

Oscilloscope Example

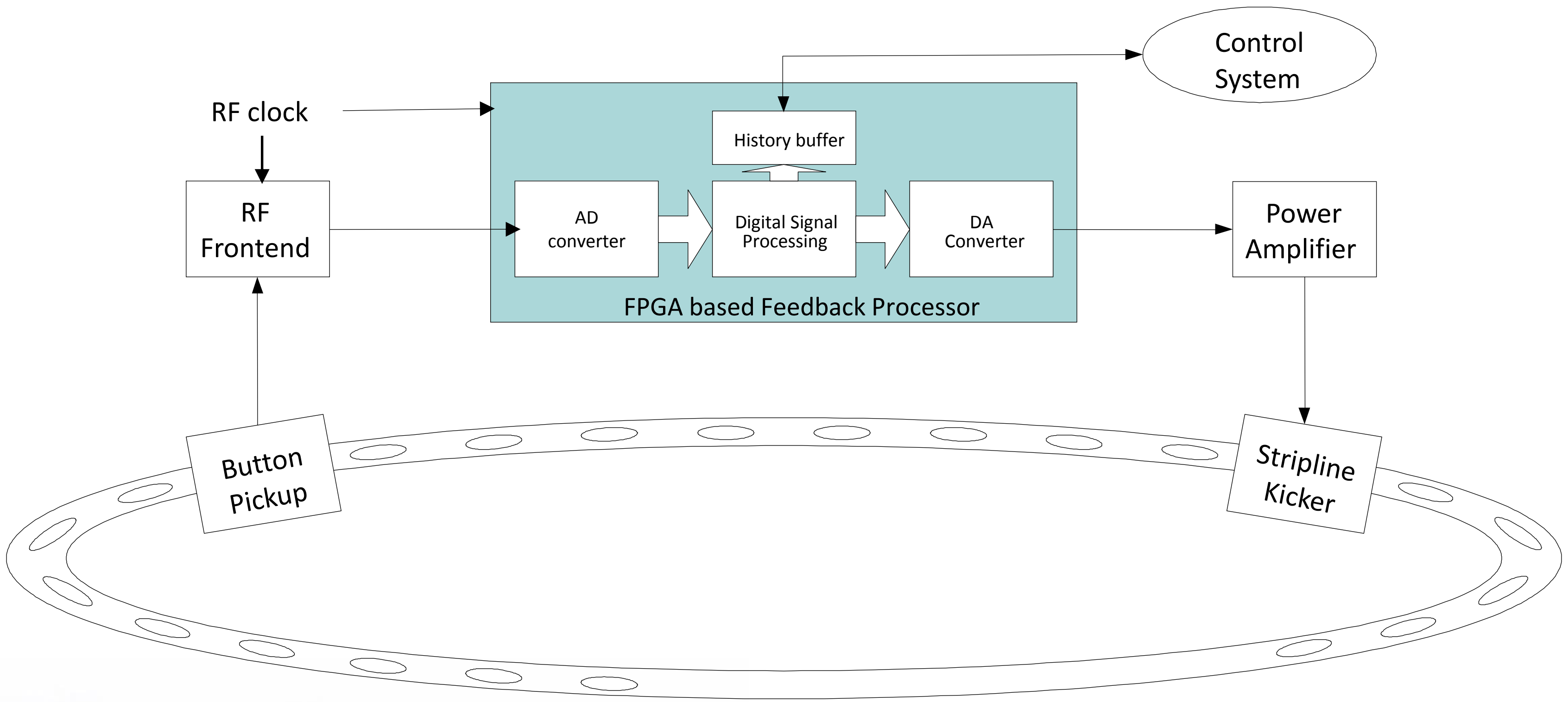
Head-Tail Instability of 1^{10} proton bunch in TEVATRON





Chou, PAC1995, p3091

Digital Bunch-by-Bunch Feedback

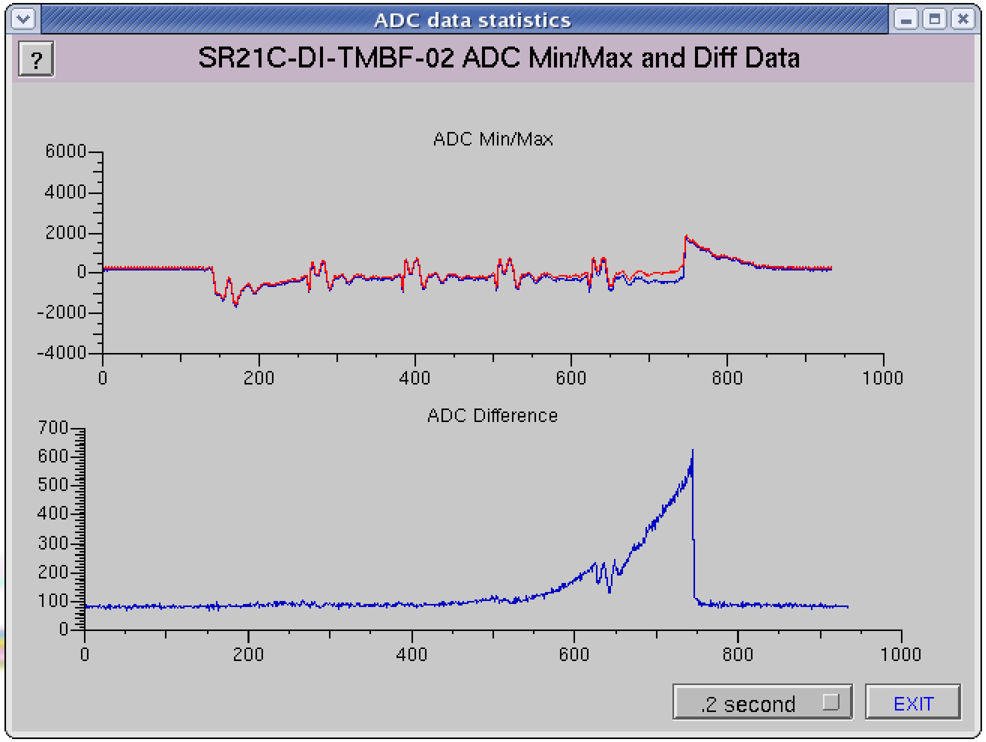


- A/D and D/A run synchronous to bunches, every bunch measured
- Provides feedback/damping of coupled bunch instabilities
- Produces a resistive (or reactive) impedance at all mode frequencies
- Longitudinal feedback similar with longitudinal kicker
- Different feedback parameters for individual bunches possible (more in next talk)

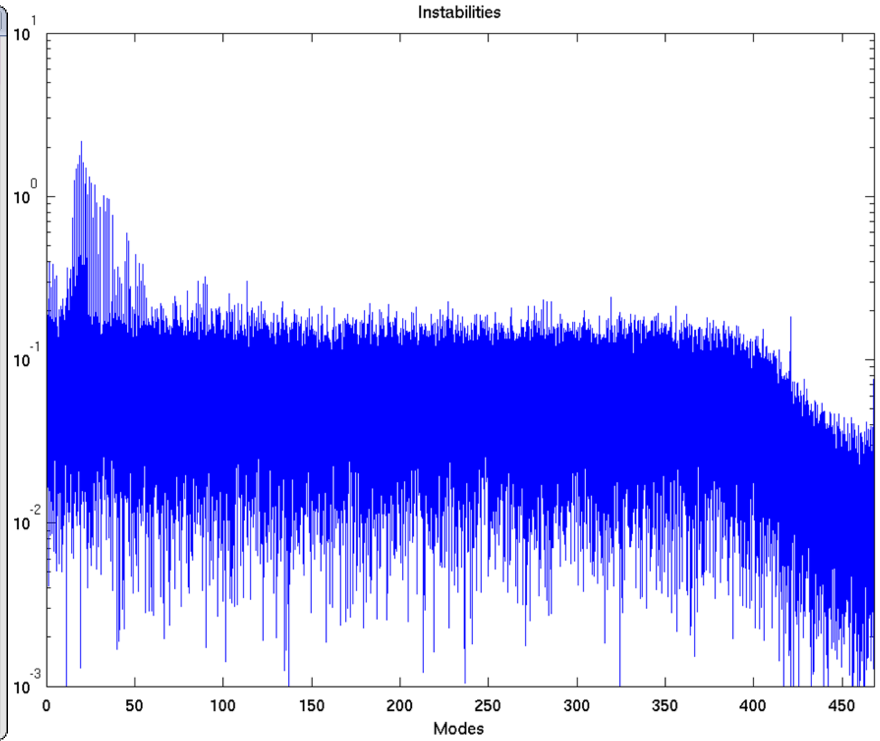
Bunch-by-Bunch Observations

Fully synchronous recording of bunch-by-bunch position
Fourier transform of long record give view like spectrum analyser
NOTE: Position reading is multiplied with bunch charge!

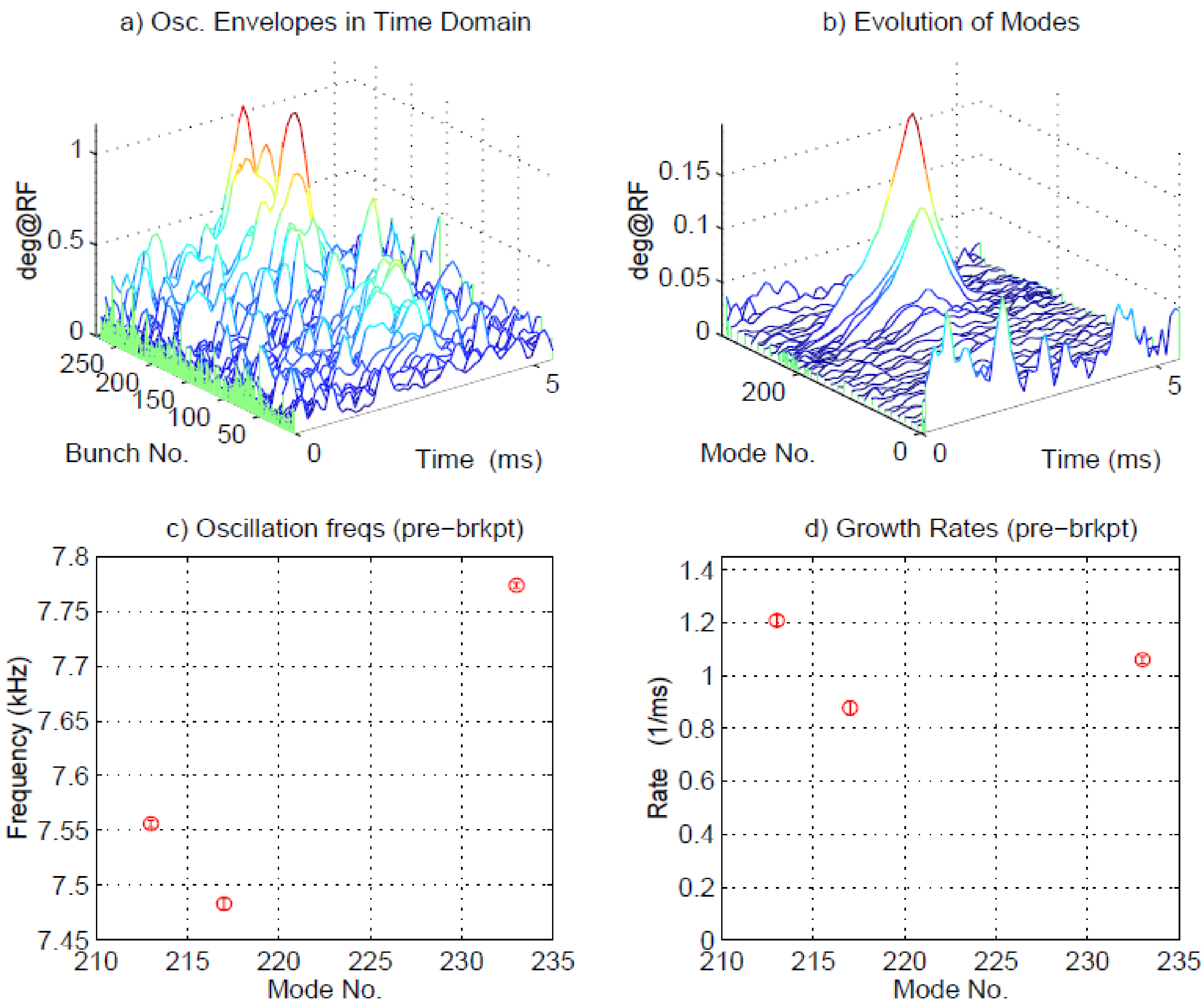
Time domain turns stacked



Spectrum with revolution harmonics removed



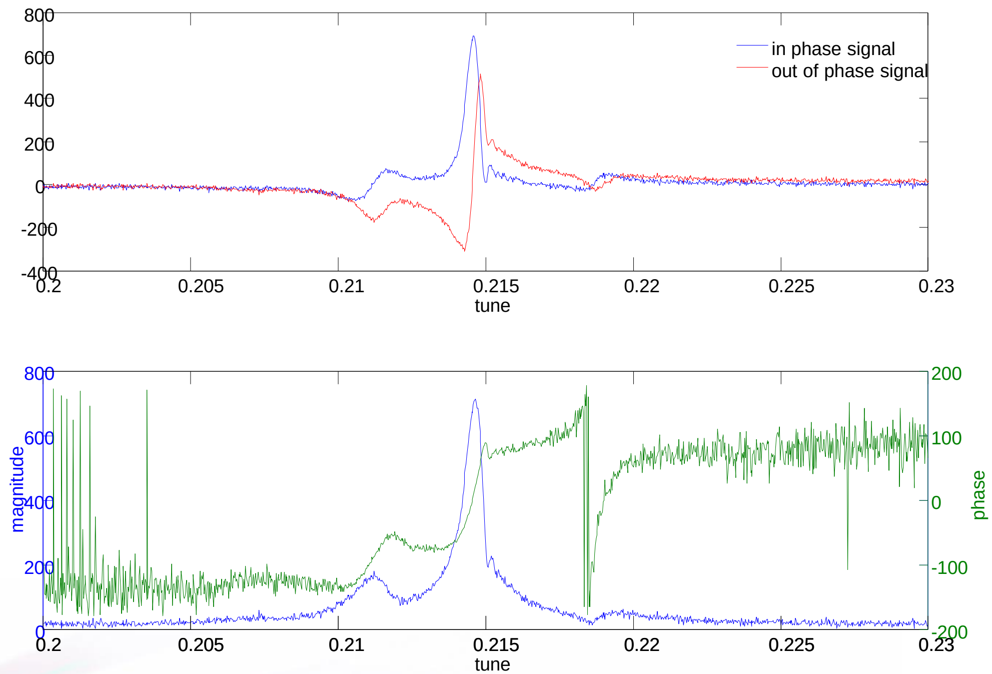
Grow-Damp Measurements

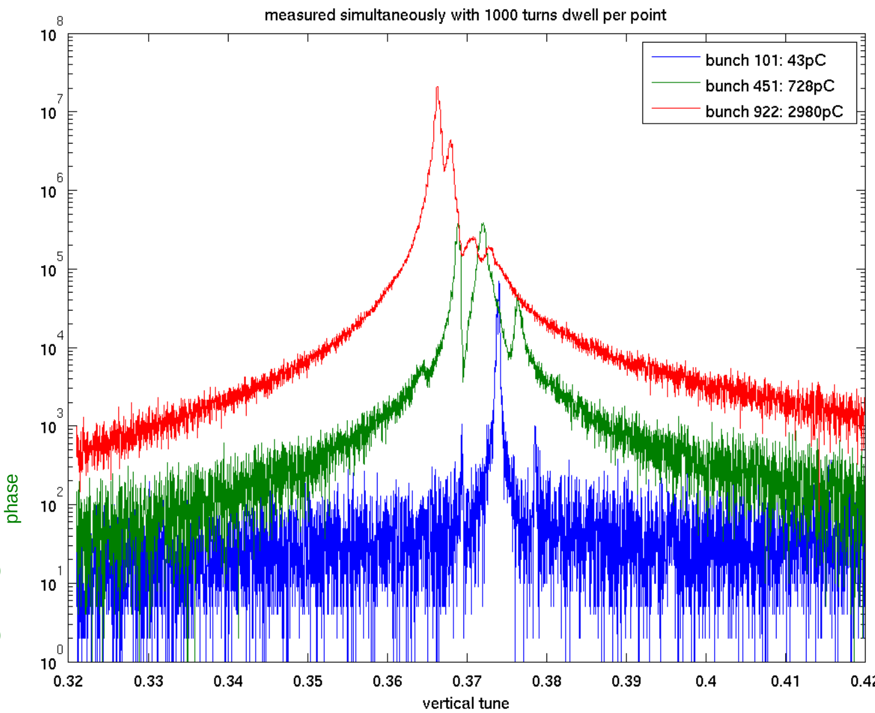


Teytelman, SLAC-R-633

Beam Transfer Function Measurement

Add numerically controlled swept oscillator to output
Detect in and out of phase components in input signal
Can be done for all bunches or individual single bunches

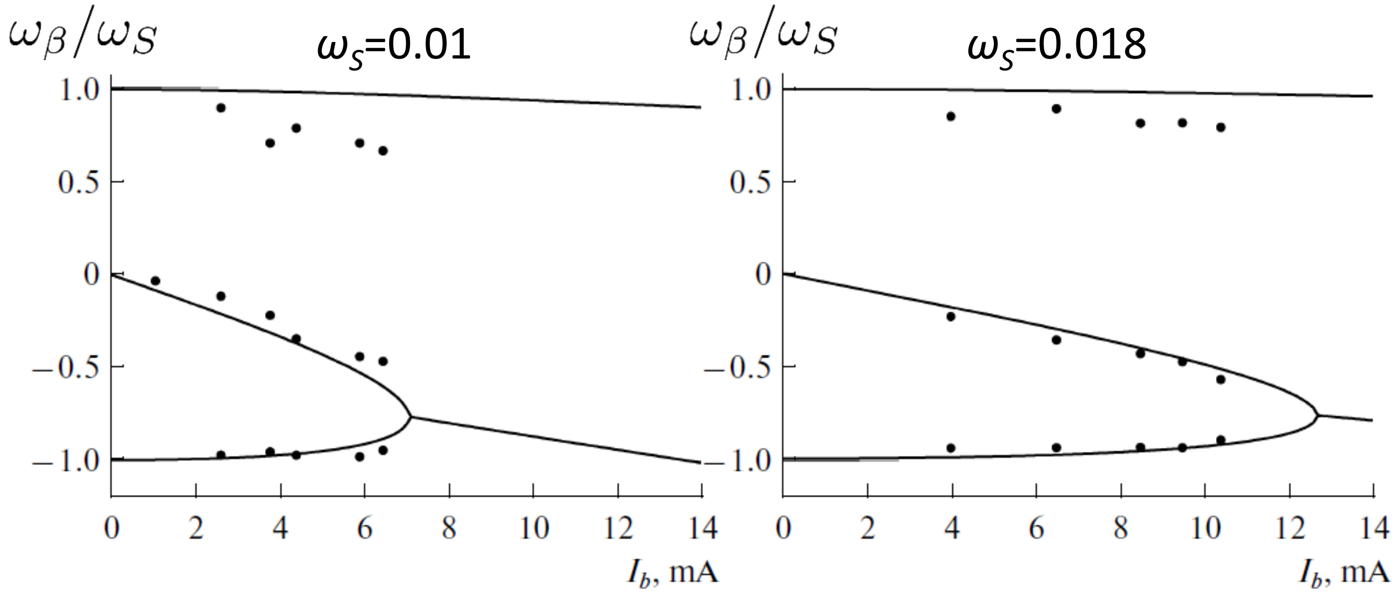


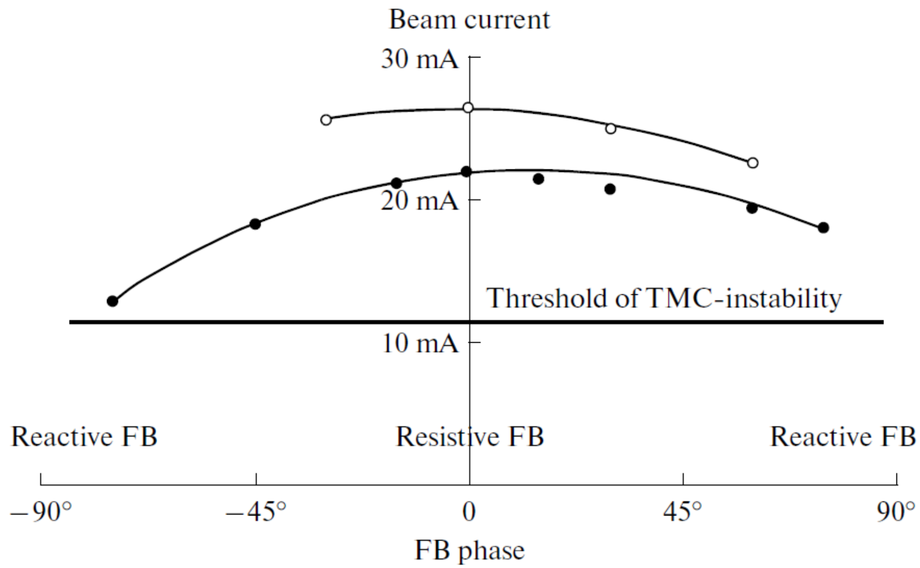


Diamond

Head-Tail Modes and Feedback

Calculated and measured frequencies shifts of the 0th, 1st and –1st head-tail modes in VEPP-4M





Smaluk, Physics of Particles and Nuclei, 2012, Vol. 43, No. 2, pp. 204

Transverse Profile Monitor

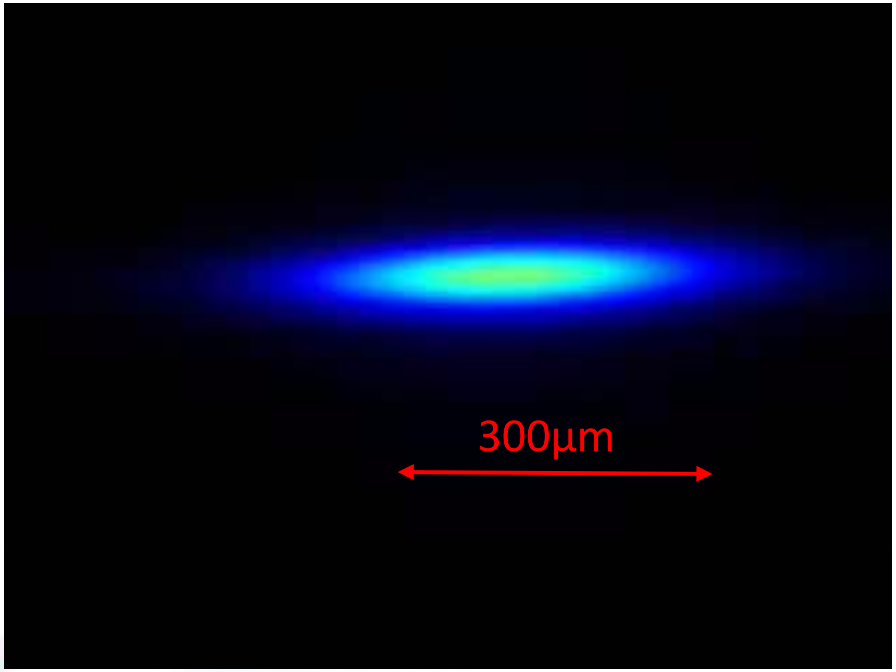
- Visible light imaging is self diffraction limited due to small opening angle of SR:

$$\sigma_0 \approx 0.3 \cdot \sqrt[3]{\lambda^2 \rho} \approx 30\mu\text{m} \;\text{ for }\; \lambda = 400\,\text{nm},\, \rho = 7.13\,\text{m}$$

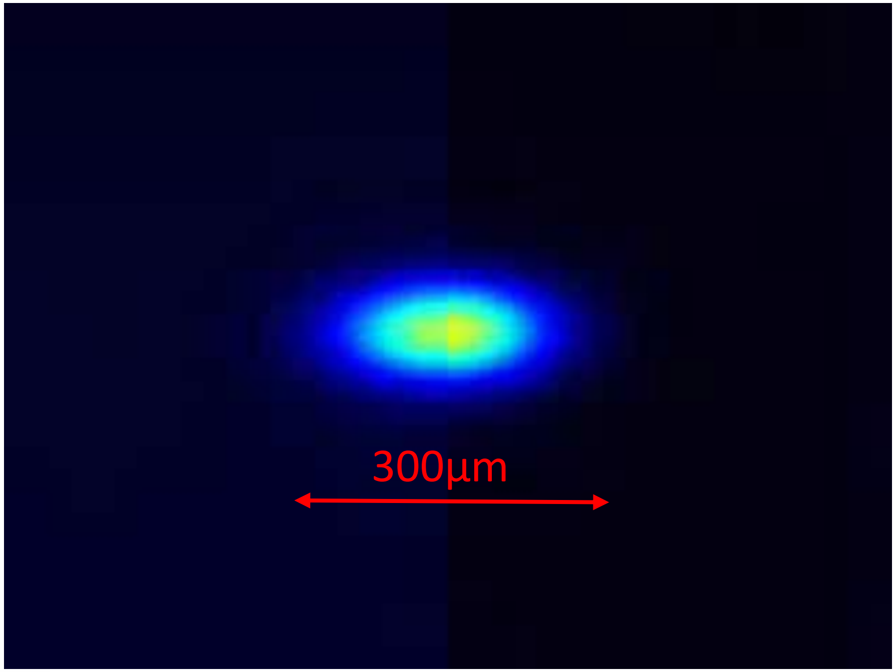
- X-ray imaging can be done with pinhole camera or CRL and scinitillator, a few µm resolution can be achieved
- Profile monitor will see any transverse instability, even longitudinal through dispersion at source point
- With two monitors at locations with different dispersion, energy spread can be calculated
- Time resolution depends on camera/detector used:
  - A few µs exposure time with many 1000 fps using CMOS
  - Single turn exposure time with low fps using gated intensified camera
  - Bunch-by-bunch 1D profile with fast X-ray detector array

Transverse Profiles from Pinhole

Transverse Instabilities at 5fps



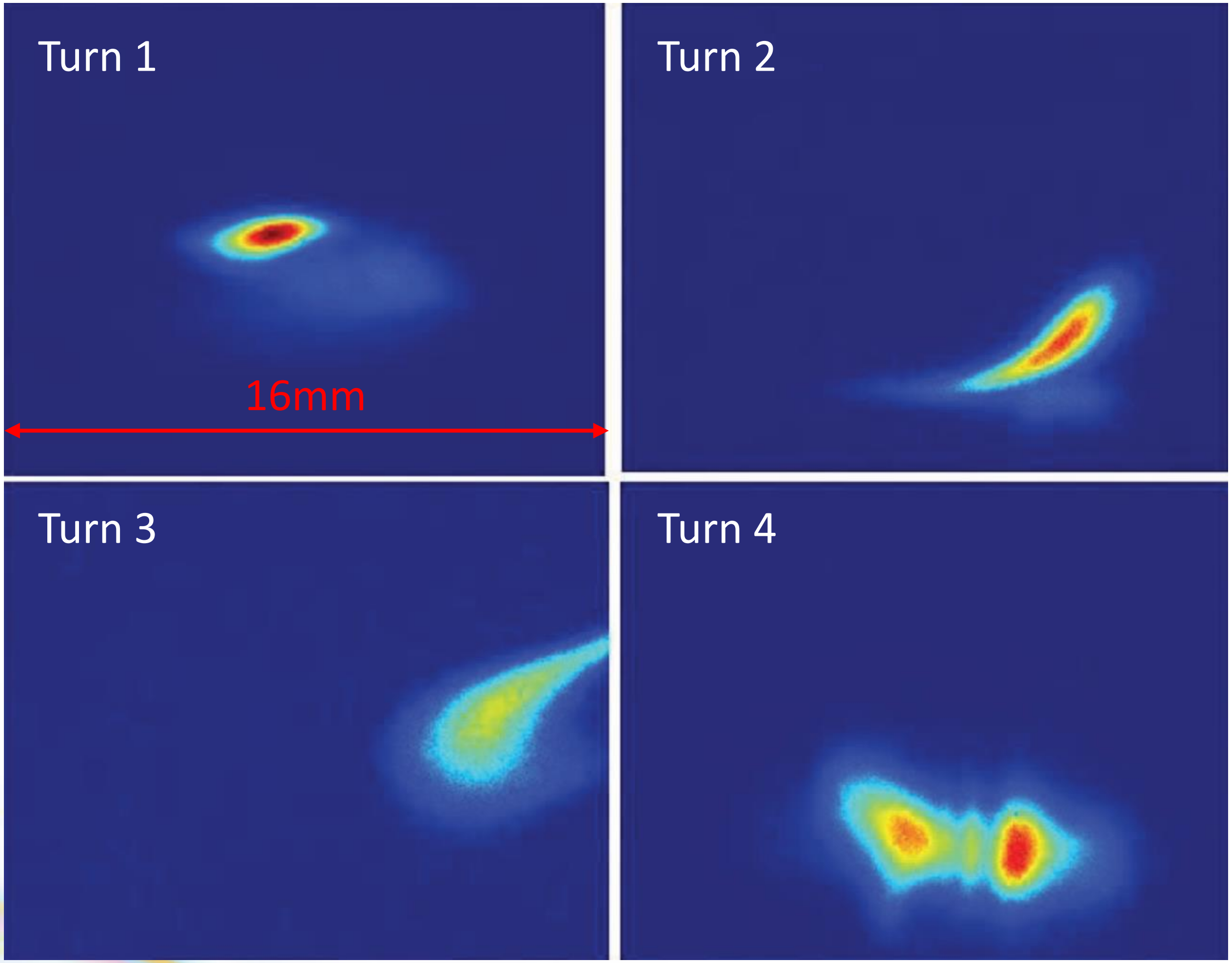
Excitation and Damping at 1200fps



Examples from the X-ray pinhole camera at Diamond

Profiles from Gated Intensified Camera

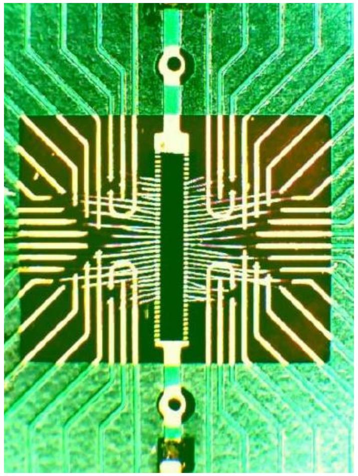
Not an instability, same time scale: turn by turn imaging of injected beam at ESRF

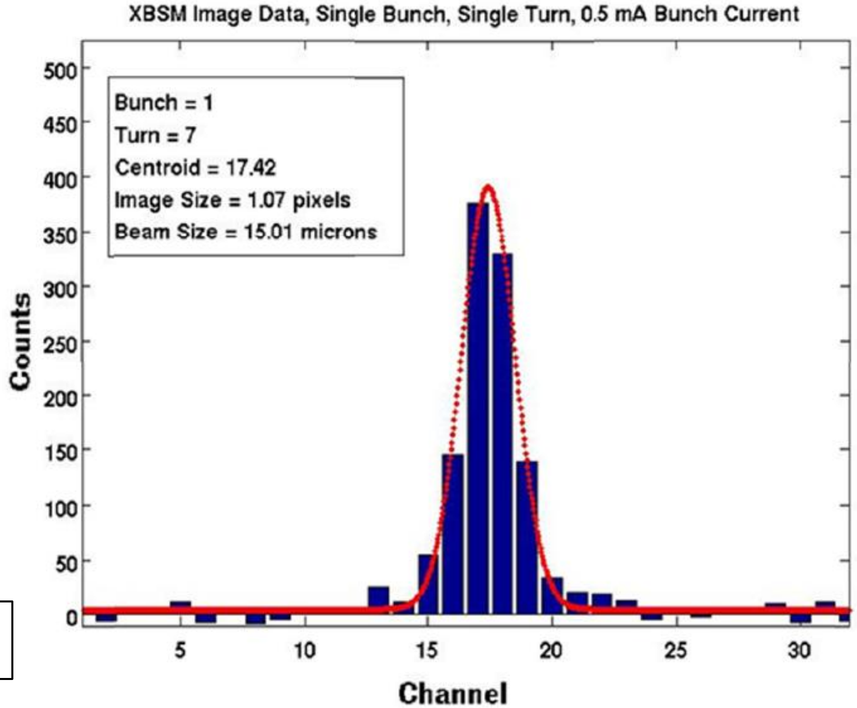


Scheidt, IPAC2013, p1143

1D X-ray Detector Array Profiler

- Vertical array of 32 InGaAs diodes with 50µm pitch
- Illuminated by pinhole with 2.5 magnification
- Produces sub ns pulses
- Each channel digitised every 4ns
- Capable of recording bunch-by-bunch profile with about 10µm RMS beam size resolution





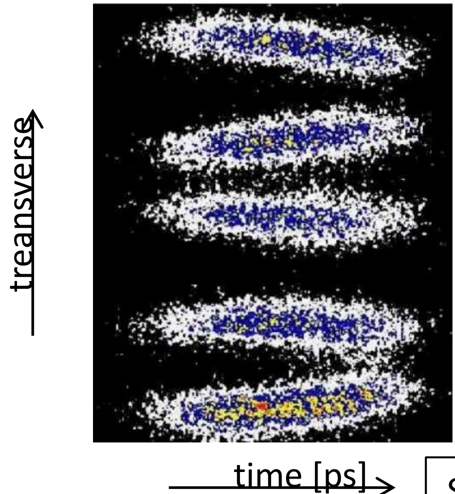
Rider, IBIC2012,p585

Streak Camera

- Takes visible light as input
- Photo cathode converts this into low energy electron bunches (a few keV)
- These are then deflected electrostatically in two axes:
  - Fast deflection often synchronous with RF giving around 1ps temporal resolution
  - Slow deflection (ns-ms time scales) to see temporal evolution
- Deflected electrons are imaged using phosphor screen and gated intensified camera
- Can be used to record only longitudinal profile/phase or also to record transverse position on ps timescales (within limits of visible light imaging...)

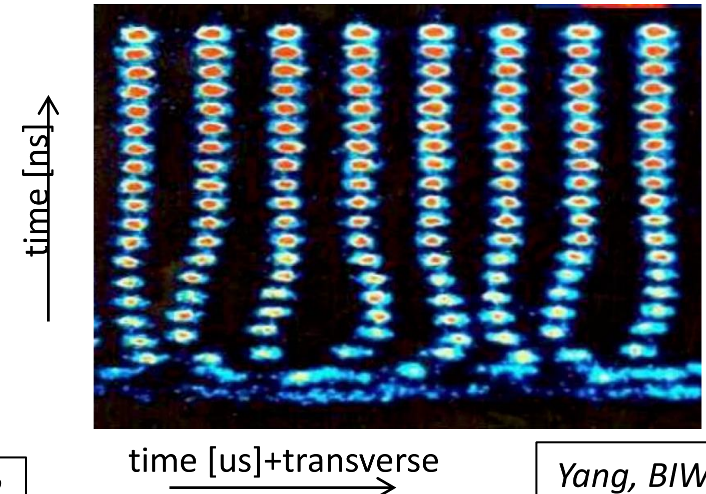
Streak Camera Examples

Vertical head tail motion



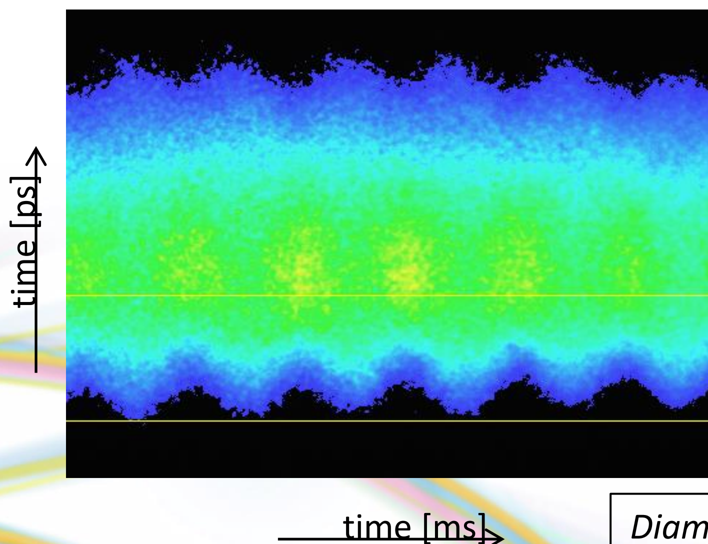
Scheidt, EPAC2000, p182

Transverse Coupled bunch motion



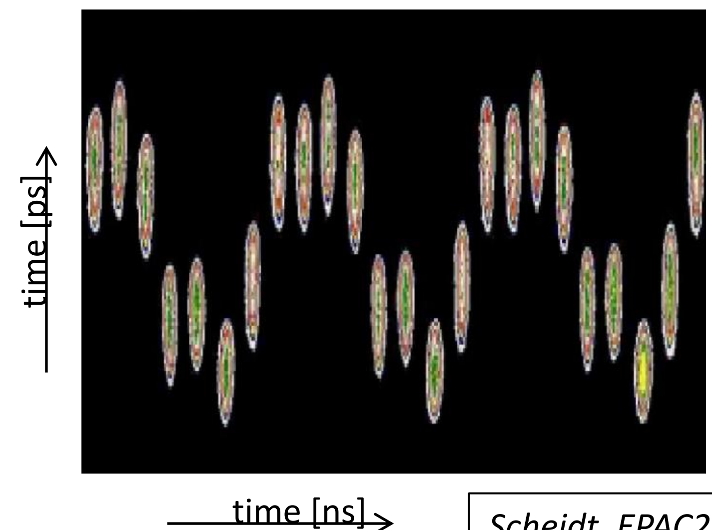
Yang, BIW1998, p229

Longitudinal profile variation during CSR bursts



Diamond

Longitudinal Coupled bunch motion



Scheidt, EPAC2000, p182

diamond

Streak Camera Limitations

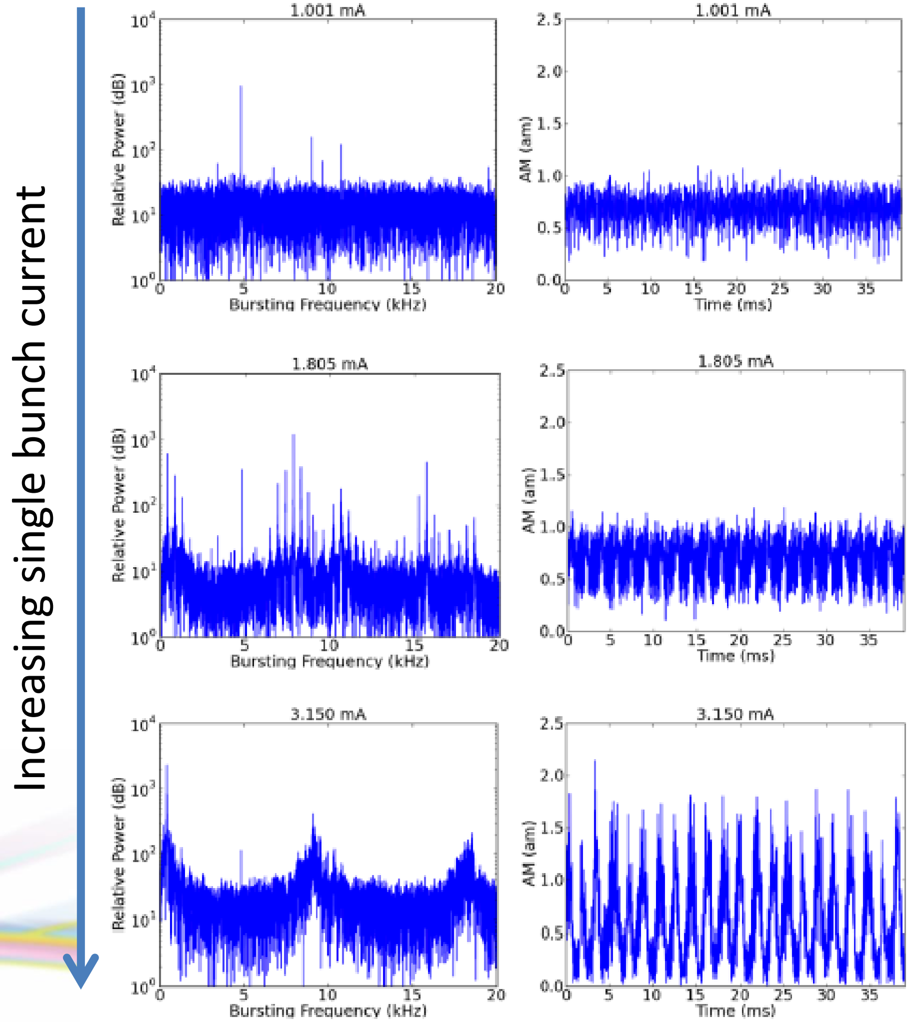
- Manufacturer specs are typically 0.5-2ps resolution
- Dispersion in the transport of the ‘white’ SR light can lead to poorer resolution:
  - Filter narrow band (but have fewer photons!)
  - Have dispersion free (reflective only) transport optics
- Space charge effects in the streak tube lead to enlarged beam (poorer resolution)
  - Operate with low flux, stack many sweeps
  - Single bunch, single turn imaging not possible with ultimate resolution!
- Phase noise on RF reference / trigger or synchrotron oscillations on beam lead to poorer resolution when stacking many sweeps.

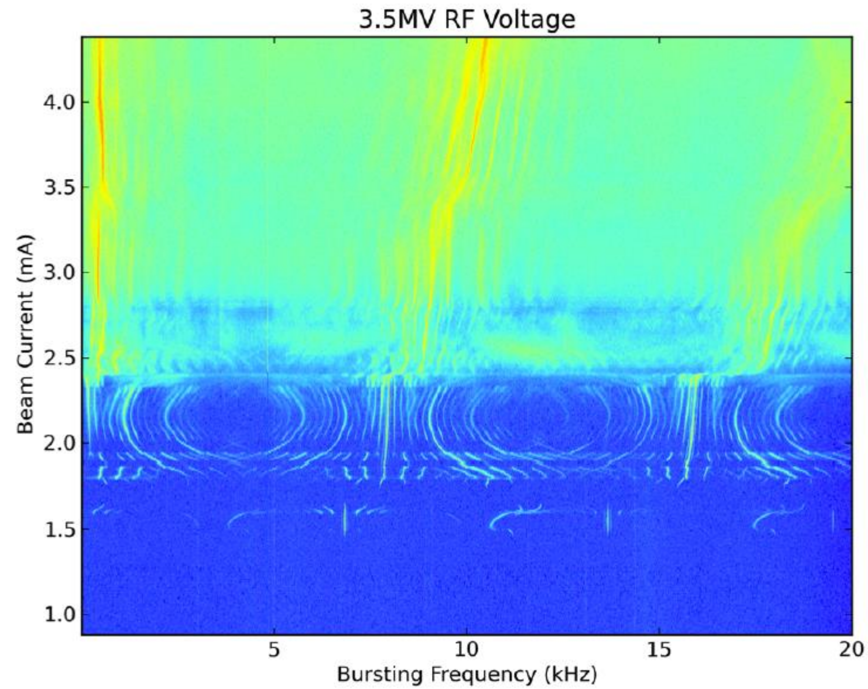
Measurement of mm-wave bursts

- Bursts of mm-wave emissions (many 10GHz to some 100GHz) can be observed as a result of coherent emissions from longitudinal density modulations of a single bunch
- These bursts are many orders of magnitude stronger than the incoherent background in a typical light source
- A variety of detectors can be used: Golay Cells, Pyrodetectors, Bolometers, Hot Electron Bolometers, Schottky diodes (more about this in talk by J Barros, and the whole next session)

mm-wave bursting time structure

Bursting from single bunch in the 60-90GHz band measured using Schottky diode detector

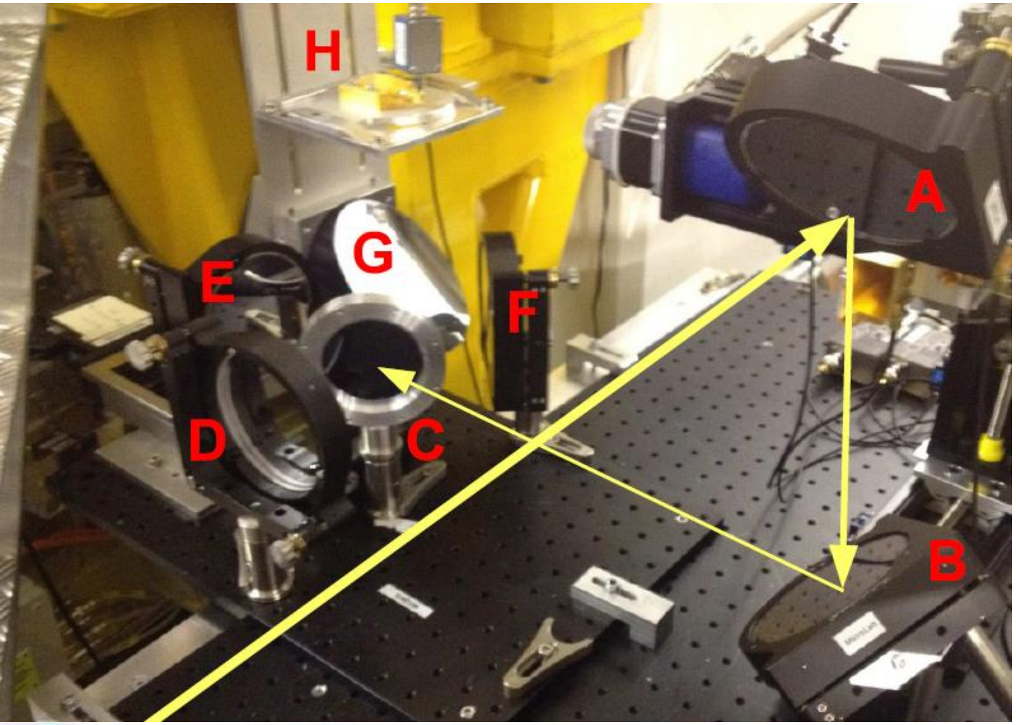


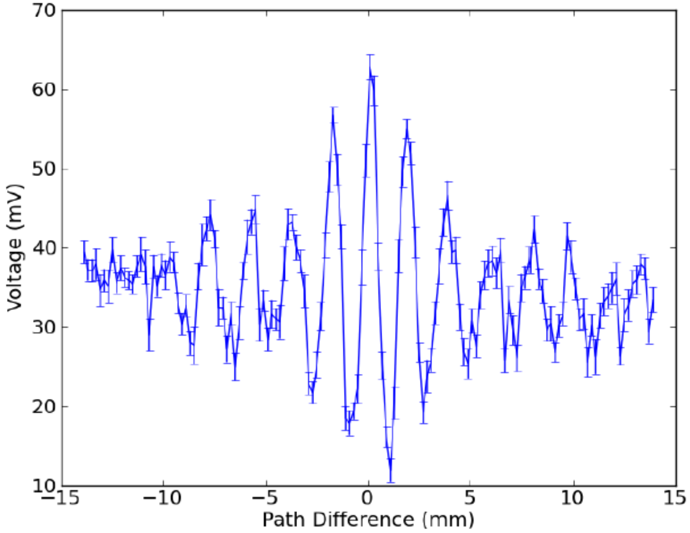


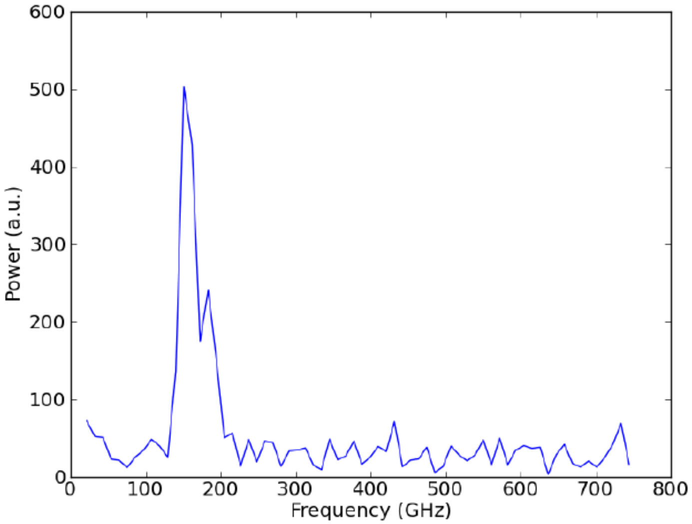
Shields, JoP Conf Series 357 (2012) 012037

mm-wave spectrum measurement

An interferometer can be used to measure the average power spectrum







Shields, IBIC2013, p143

Summary

Source	Instrument	Single Bunch		Coupled Bunch	
		longitudinal	transverse	longitudinal	transverse
BPM pickup	Spectrum Analyser	Maybe (if bandwidth sufficient)	Maybe (if bandwidth sufficient)	YES	YES
	Oscilloscope	Maybe (if bandwidth sufficient)	Maybe (if bandwidth sufficient)	YES	YES
	Bunch-by-Bunch FB	NO	Maybe	YES	YES
Synchrotron Radiation Port	Transverse Profile	Indirect through dispersion	YES	Indirect through dispersion	YES
	Streak Camera	Maybe (if resolution sufficient)	Maybe (if resolution sufficient)	YES	YES
	mm-wave detector	YES	NO	NO	NO

Potential Future Developments

- Transverse imaging capable of resolving **both** small transverse profile and bunch by bunch (or at least turn by turn). Maybe X-ray pinhole and
  - gated intensified camera
  - fast line camera or X-ray detector
  - X-ray streak camera
- Turn-by-turn spectrometer for mm-wave bursts
- Streak cameras with better resolution, especially in single shot
- Digital Feedback inside bunch? Yes for Hadrons, probably not for the bunch lengths in lepton machines...