Diagnosing instabilities, HOMs

How to use fast diagnostics to study coherent (mostly coupled bunch) instabilities

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- Outline:
  - Mode Patterns/Multibunch
  - Streak Camera Pictures of Instabilities
  - Feedback Systems/Multibunch Diagnostics
  - Two Stream Instabilities

Principle of streak camera

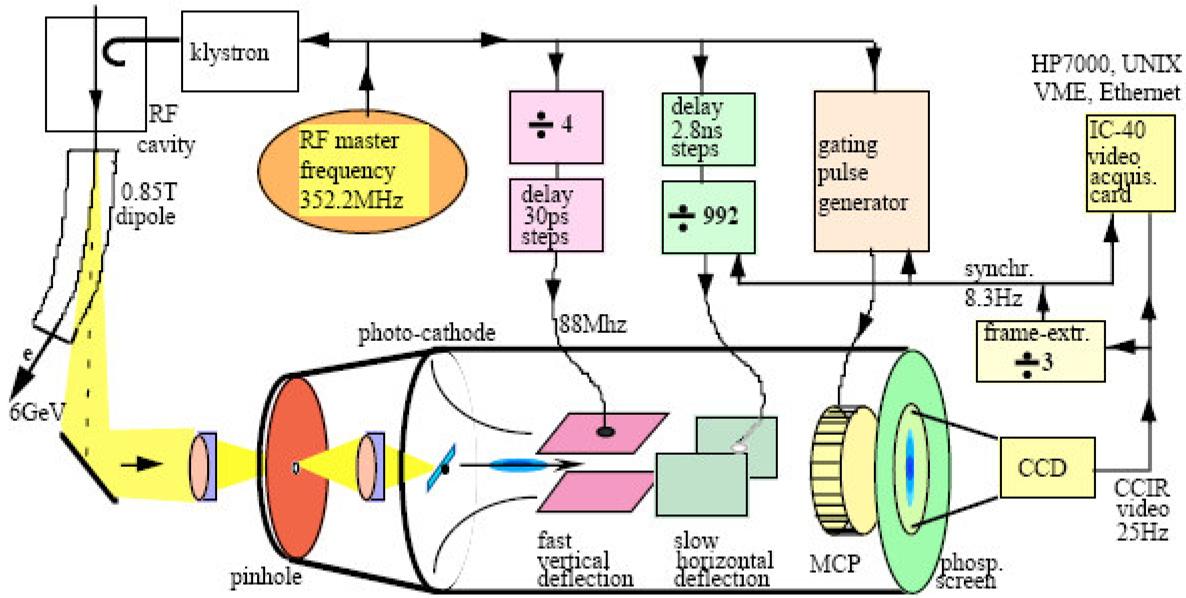
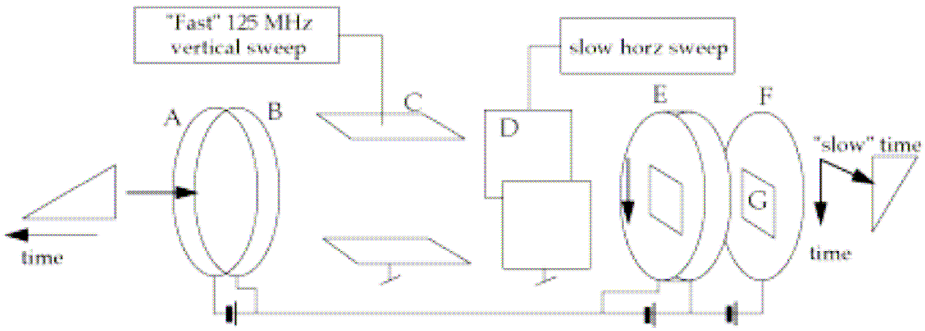
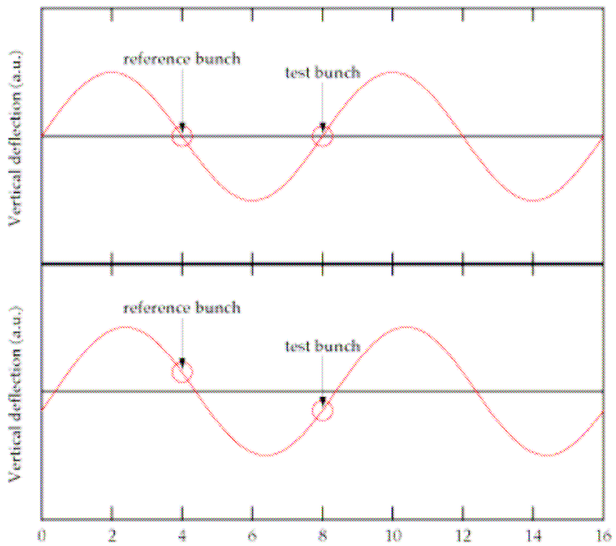


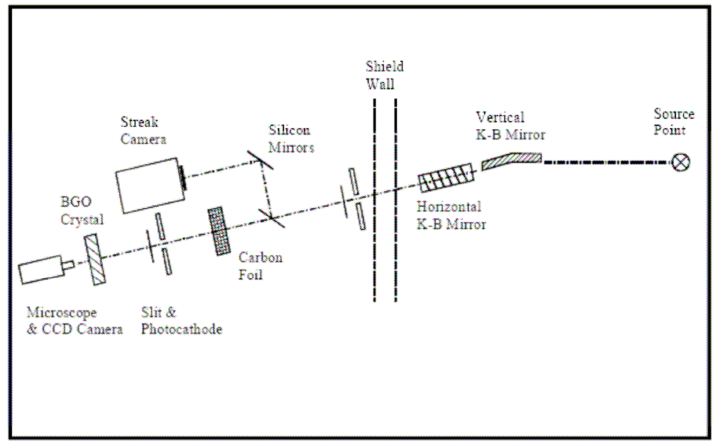
Figure: 1 Synchronisation of the Streak Camera system

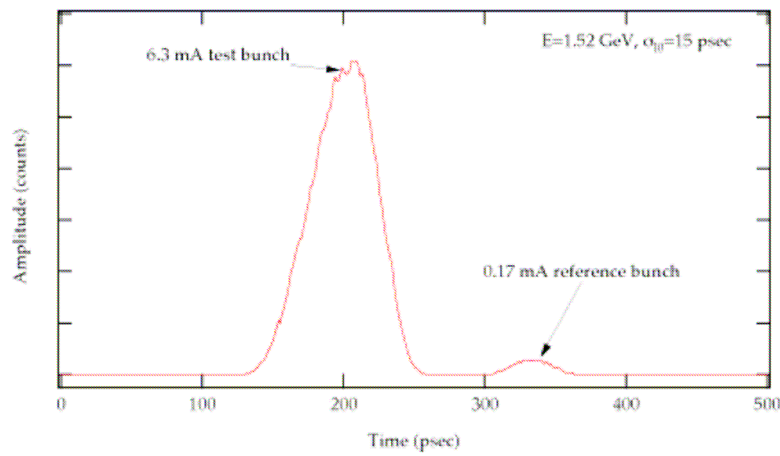
- Convert light signal into electron beam (photo cathode)
- Accelerate electrons
- Use fast deflection to translate time delay into position difference
- In many ways similar to CRT …

Streak Camera







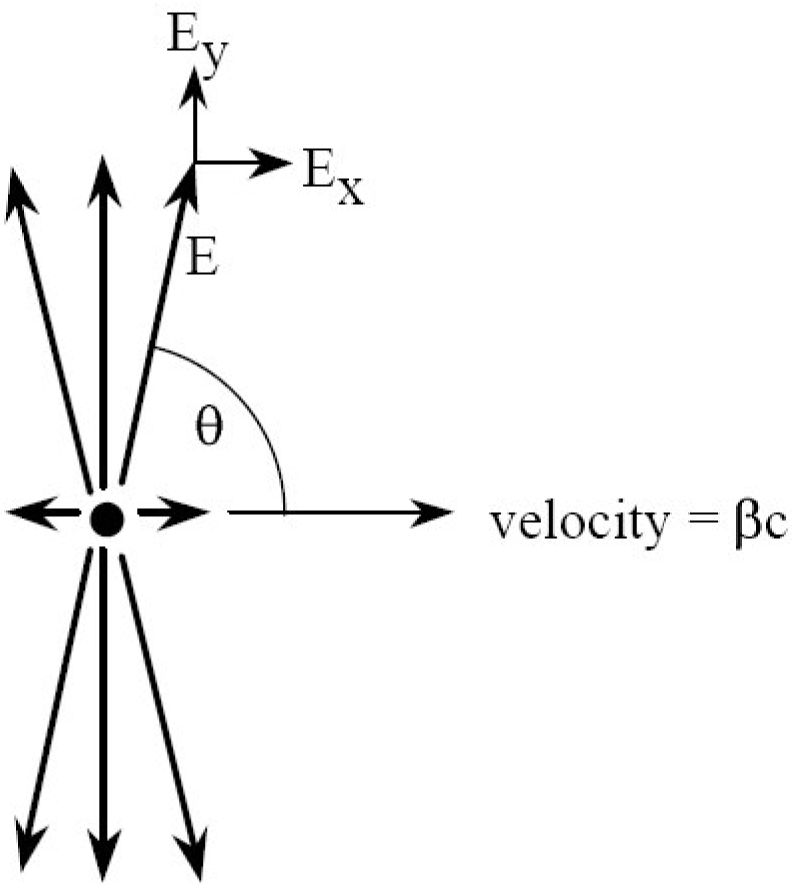


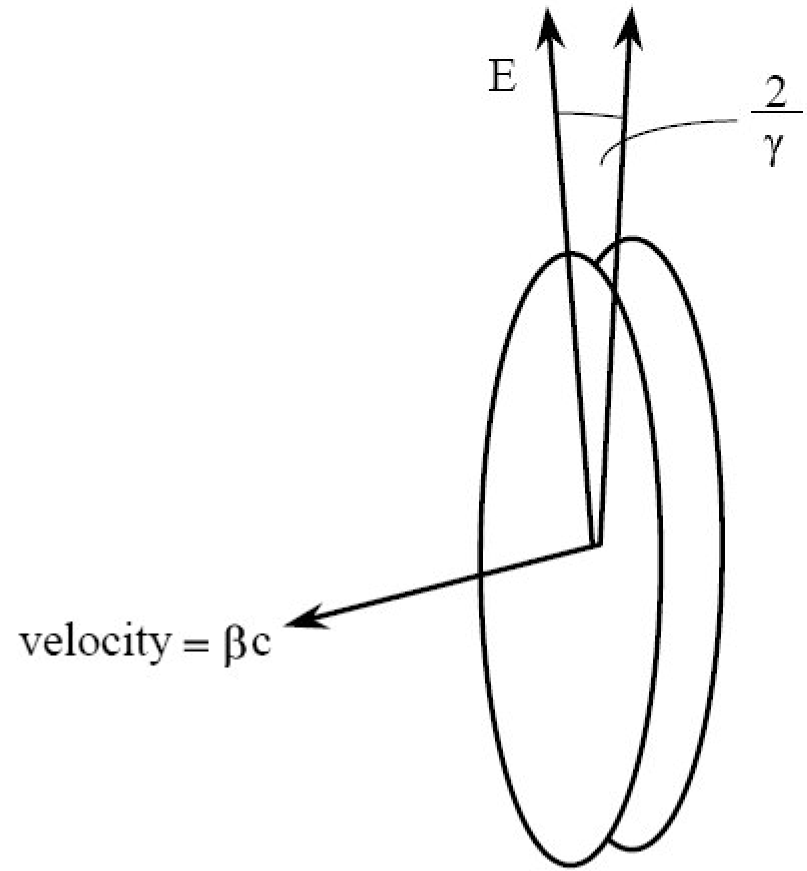
- Allows fast diagnostic of contamination in all buckets on 0.1% level

Instabilities

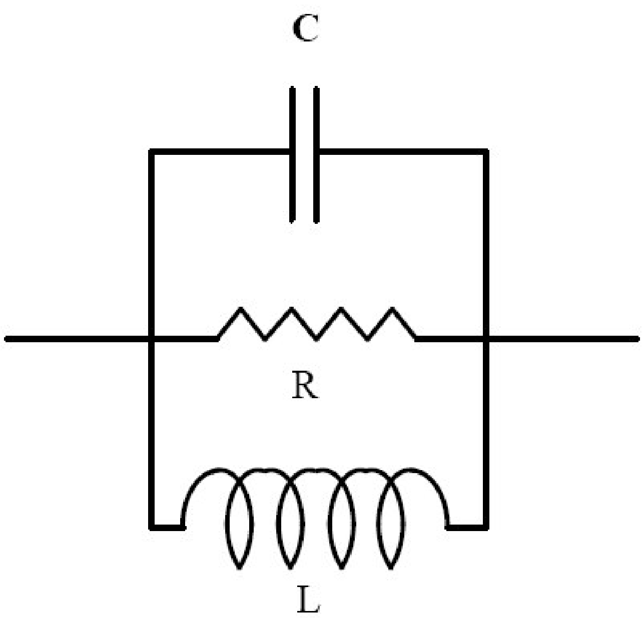
- Instabilities are coherent processes leading to usually exponential amplitude growth
  - Coherent means that an ensemble of particles is involved (either bunch, many bunches, cw beam, …)
  - This is different from single particle effects like the interaction of individual beam particles with external fields (magnets, cavities)
- Very important topic for any high current accelerator, storage ring, …
- Classification according to
  - Single bunch – Multibunch
  - Longitudinal – Transverse
  - Impedance type: Narrow Band – Broadband
    - Higher modes in cavities, resonant structures – resistive wall, step transitions, tapers, …
  - Shape of oscillation: Dipole, Quadrupole, …

Impedances – Interaction with walls, steps, cavities, …



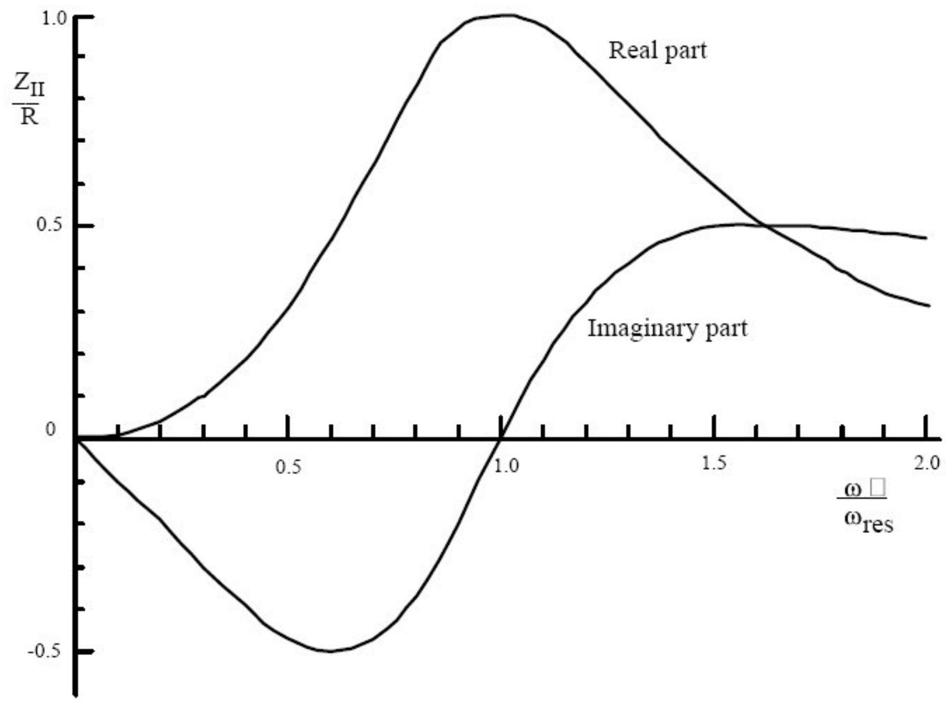


Broadband Impedance – Equivalence to discrete circuit



$$Z_{II} = \frac{R}{1 + jQ\left(\frac{\omega_{res}}{\omega} - \frac{\omega}{\omega_{res}}\right)}$$

$$\omega_{res} = \frac{1}{\sqrt{LC}}, \qquad Q = R\sqrt{\frac{C}{L}}$$



Instabilities: Equations of motion

- Harmonic oscillator with driving term

$$\ddot{u} + \omega_0^2 u = Gu = (G_R + jG_I)u$$

- Solution:

$$u = u_0 \exp(j\omega_n t)$$

$$\omega_n = \omega_0 + \Delta\omega, \text{and } \Delta\omega = -\frac{G}{2\omega_0} = -\frac{G_R}{2\omega_0} - j\frac{G_I}{2\omega_0}$$

$$u = u_0 \exp(j\omega_0 t) \cdot \exp\left(-\frac{jG_R}{2\omega_0}t\right) \cdot \exp\left(+\frac{G_I}{2\omega_0}t\right).$$

- Growth/Damping coefficient

$$\alpha = \frac{1}{\tau} = -\operatorname{Im}(\Delta\omega) = +\frac{G_I}{2\omega_0}$$

Driving Force - Impedance

- In case of instabilities, driving ‘force’ is normally an induced ‘force’ such as voltage induced by passage of the charged beam itself.
- Since force is induced by the beam, it can only have components at frequencies corresponding to the modes of oscillation of the beam itself.
- Thus the force results from the spectrum of the beam oscillation ‘sampling’ the **impedance** Z seen by the beam.
- In certain cases the induced driving force is fairly obvious and can be derived almost by inspection, but in most cases the derivation is more complicated.
- Stability is determined by the sign of the **real part of the impedance.**
- Stability is calculated by evaluating the frequency dependence of the impedance seen by the beam and the power spectrum of the beam oscillations which ‘sample’ the impedance to produce an induced normalized force.

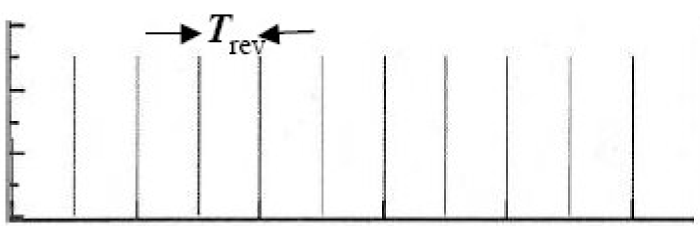
Bunch spectrum

Using a spectrum analyzer with a BPM can yield a wealth of information on beam optics and stability. A single bunch with charge q in a storage ring with a revolution time T_{rev} gives the following signal on an oscilloscope

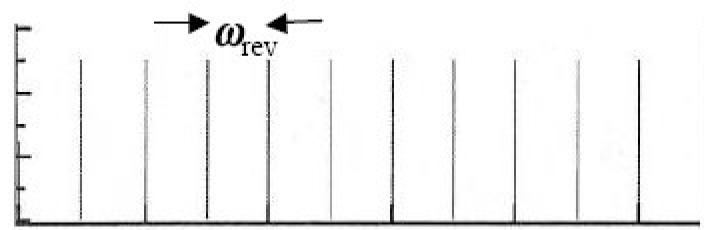
$$I(t) = \sum_{n=-\infty}^{\infty} q\delta(t - nT_{\text{rev}}),$$

where I'm assuming a zero-length bunch. A spectrum analyzer would see the Fourier transform of this,

$$I(\omega) = \sum_{n=-\infty}^{\infty} q\omega_{\text{rev}}\delta(\omega - n\omega_{\text{rev}})$$



Time

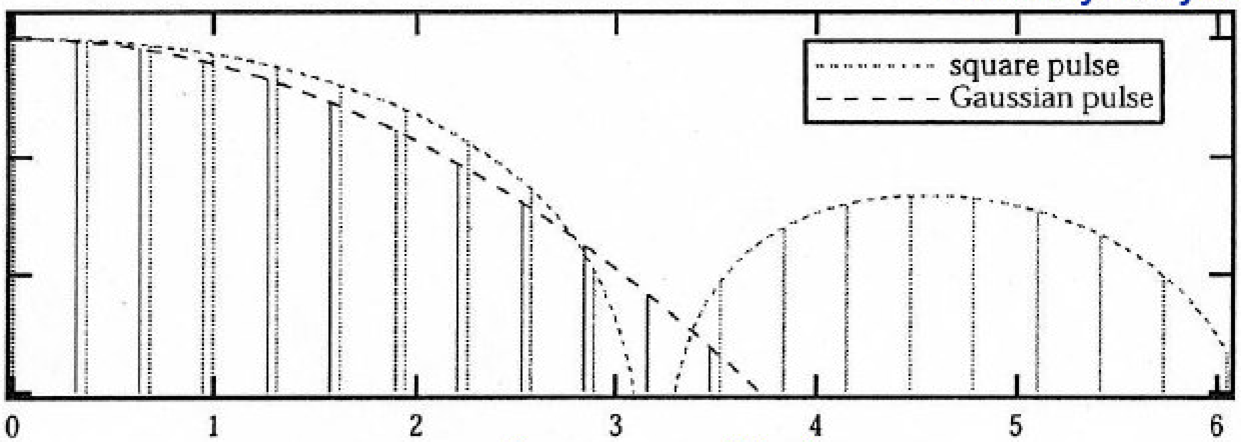


Frequency

Dependence of Spectrum on Bunch Length

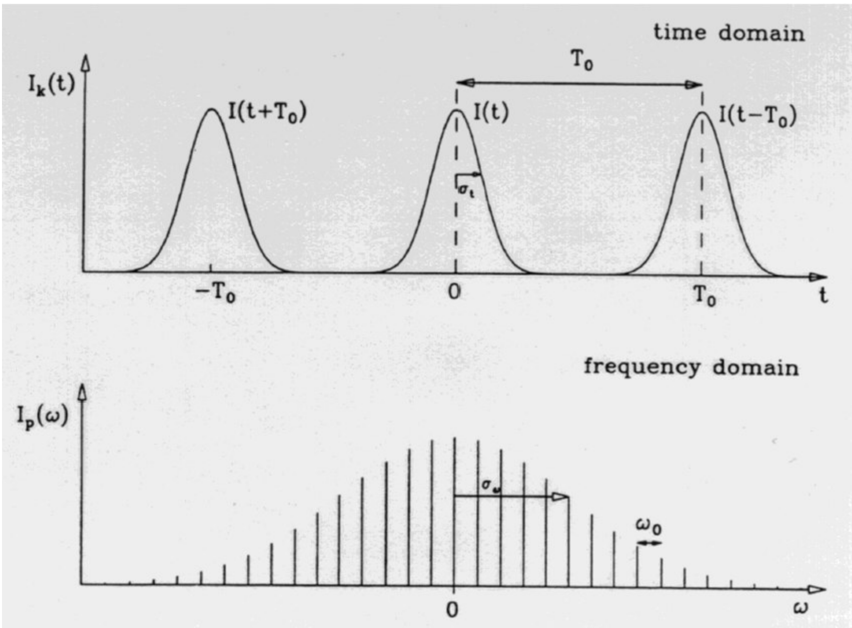
For finite bunch length, the single bunch spectrum rolls off as the Fourier transform of the longitudinal bunch profile (Gaussian for e-rings).

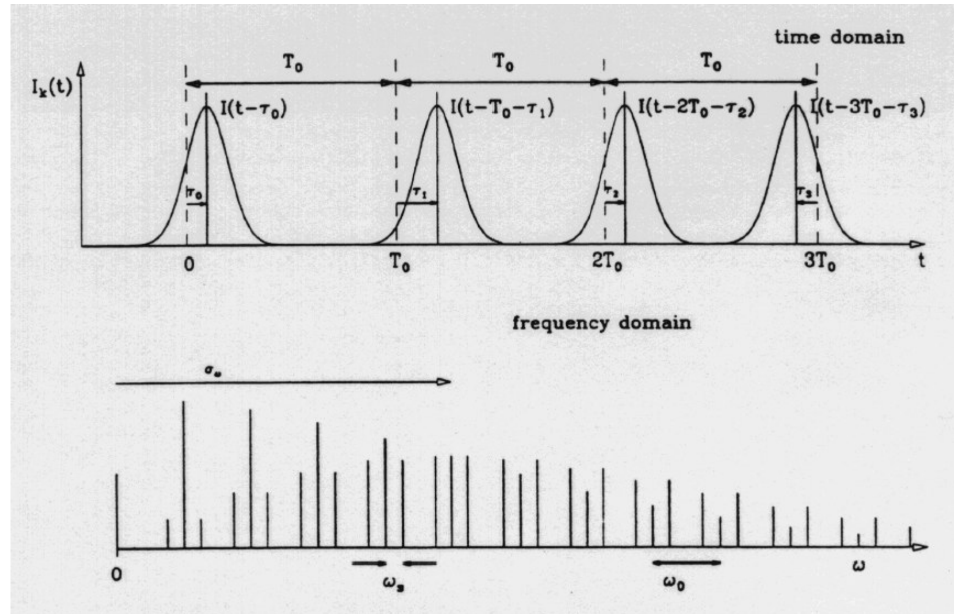
Courtesy J. Byrd



For SPEAR3 σ_z = 4.5 mm, so c/σ_z = 67 GHz.

Sideband in frequency spectrum





- Oscillations of the bunches show up as additional spectral lines (sidebands)
  - Synchrotron oscillations (Energy – Phase/Arrival Time) on sum signal
  - Betatron oscillations (transverse position – angle) on difference signal
- Separation from revolution harmonics is fractional synchrotron tune or betatron tune

Examples of instabilities (excited sidebands)

- Specific sidebands being excited correspond to specific instability characteristics:
  - Mode number, dipole/quadrupole/…,
  - Frequency of the HOM driving the instability (modulo RF frequency)

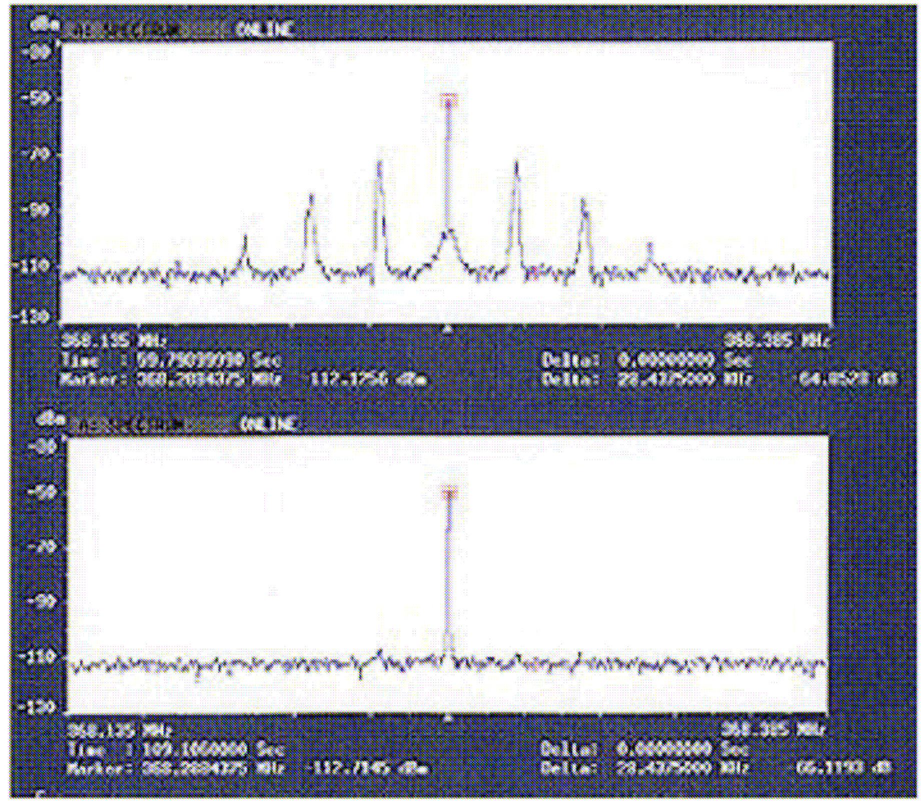
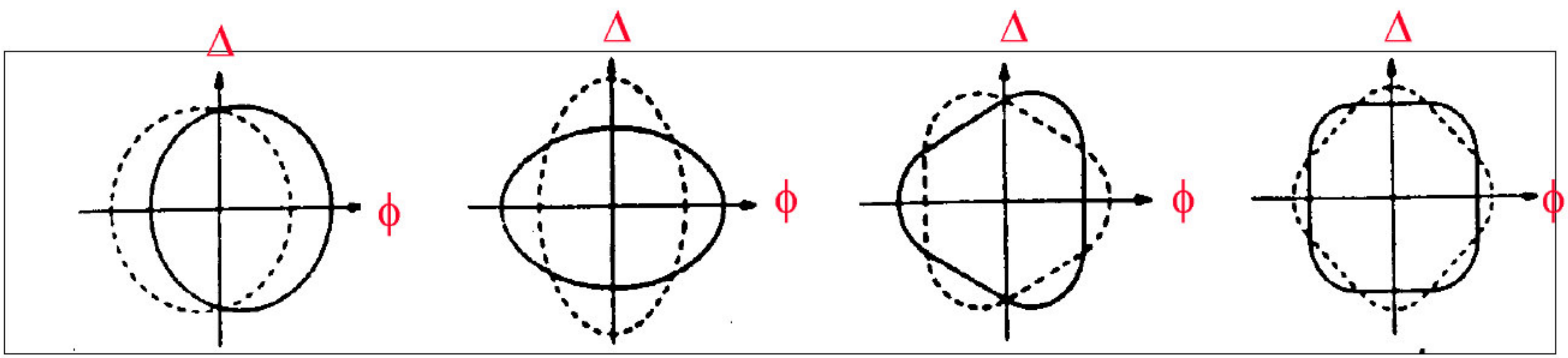


Figure 3: Longitudinal pick-up signal spectrum of 30 bunches with feedback off - feedback on.

Dipole, Quadrupole, … Oscillations

❖ There are different shapes of oscillations:
  - Dipole – ‘rigid body’
  - Quadrupole – shape/size
  - Sextupole …



m =1
dipole mode

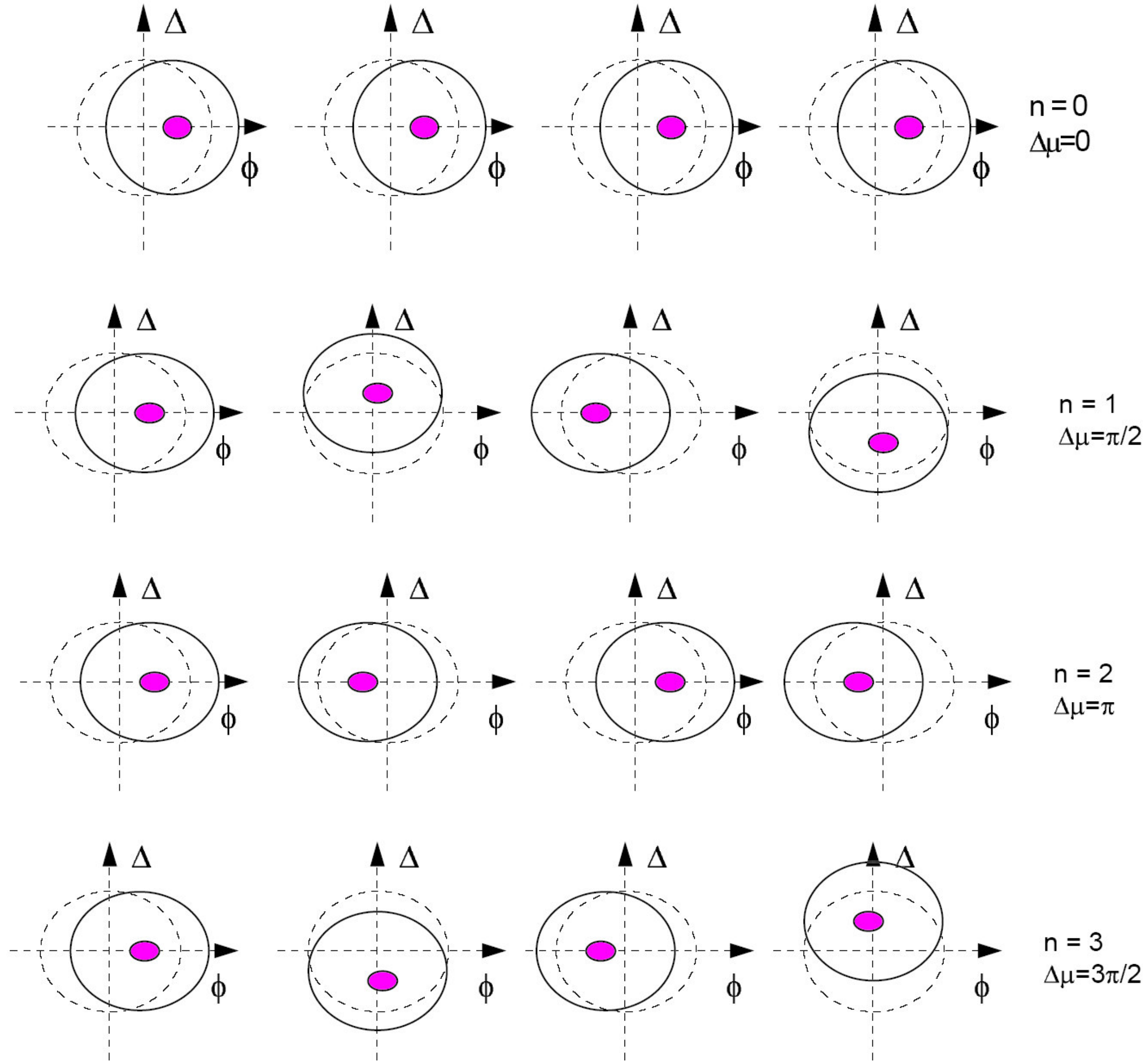
m =2
quadrupole mode

m =3
sextupole mode

m =4
octupole mode

Multi Bunch Instabilities: Mode Number

- Depending on the frequency of the driving impedance, instabilities with different mode number, i.e. different phase shift from one bunch to the next are driven.
- Example for dipole oscillations of 4 bunches:



Some Streak camera pictures of instabilities

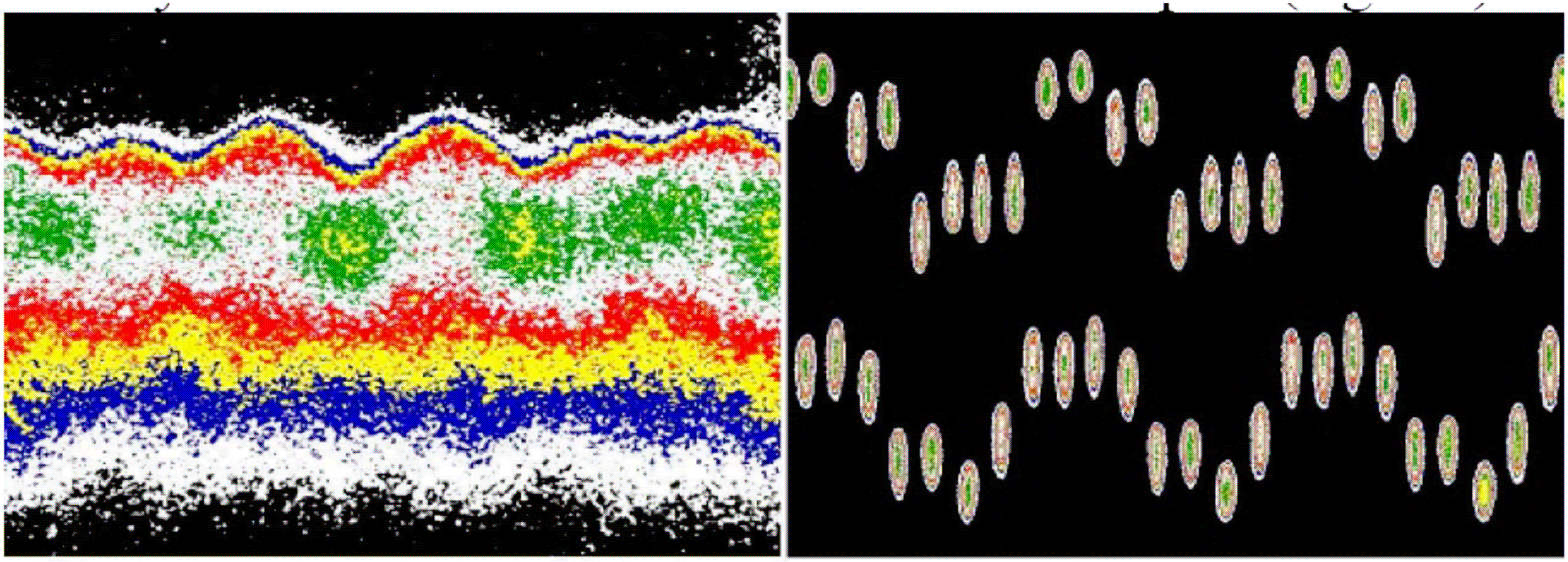


Fig.3a (left) : ESRF at low α : bunch length fluctuation
Fig. 3b (right) : ESRF HOMs causing longit. instabilities

Streak Camera II

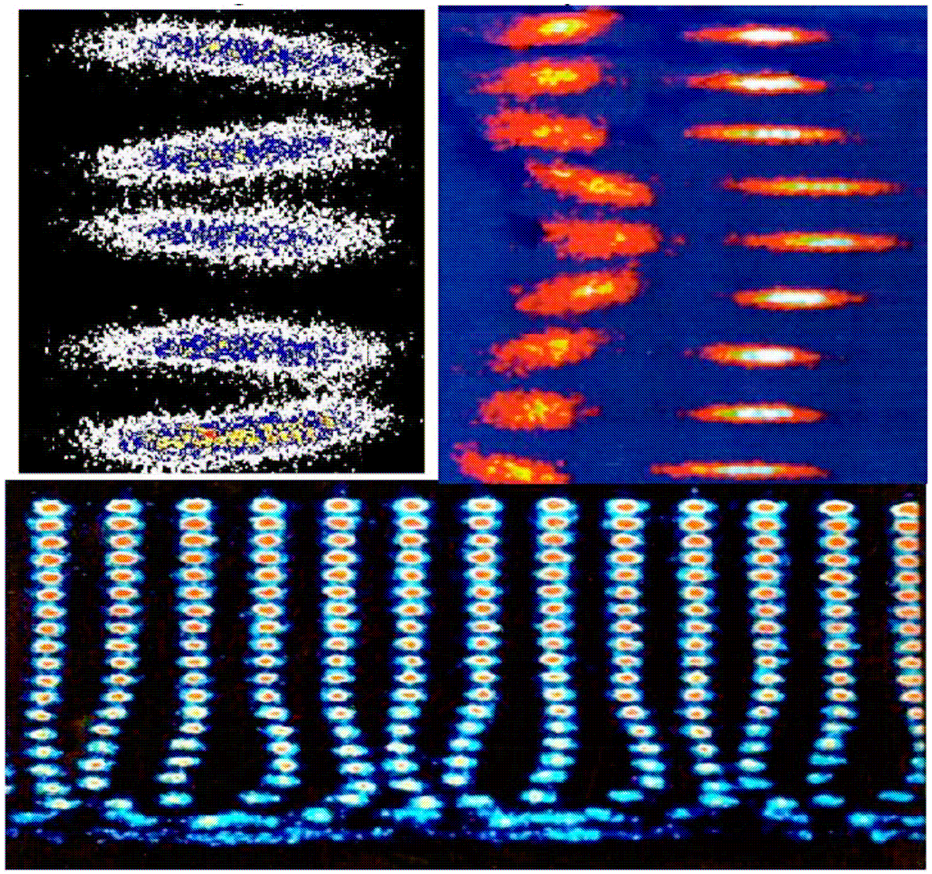
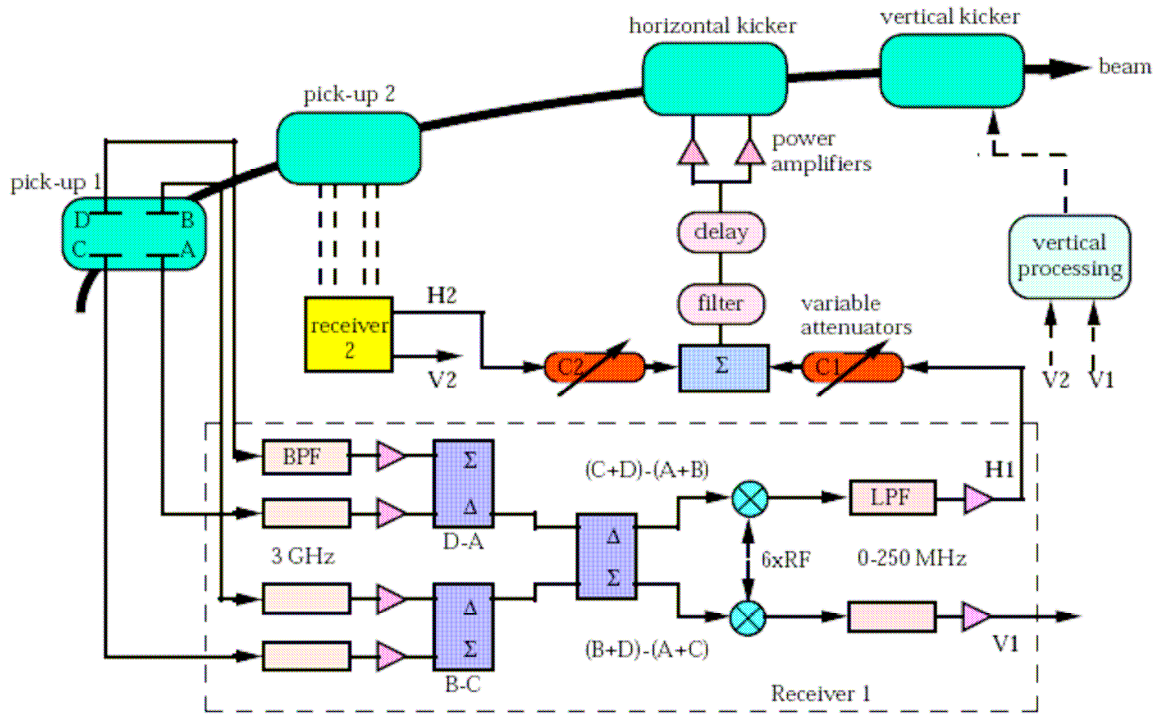


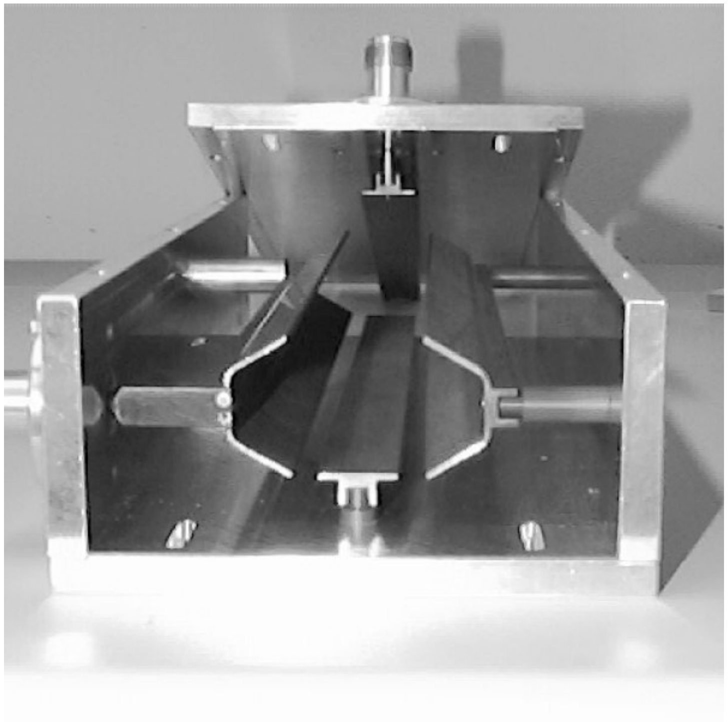
Fig.6a (left) : ESRF five turns of single bunch showing vertical Head-Tail instability,
Fig.6b (right) : LEP top & side views of bunch over 9 turns showing vertical Head-Tail effects, transverse motions and bunch length fluctuations,
Fig.6c (bottom) : APS horizontal coherent motions at trail of the 60ns filling pattern over 13 turns

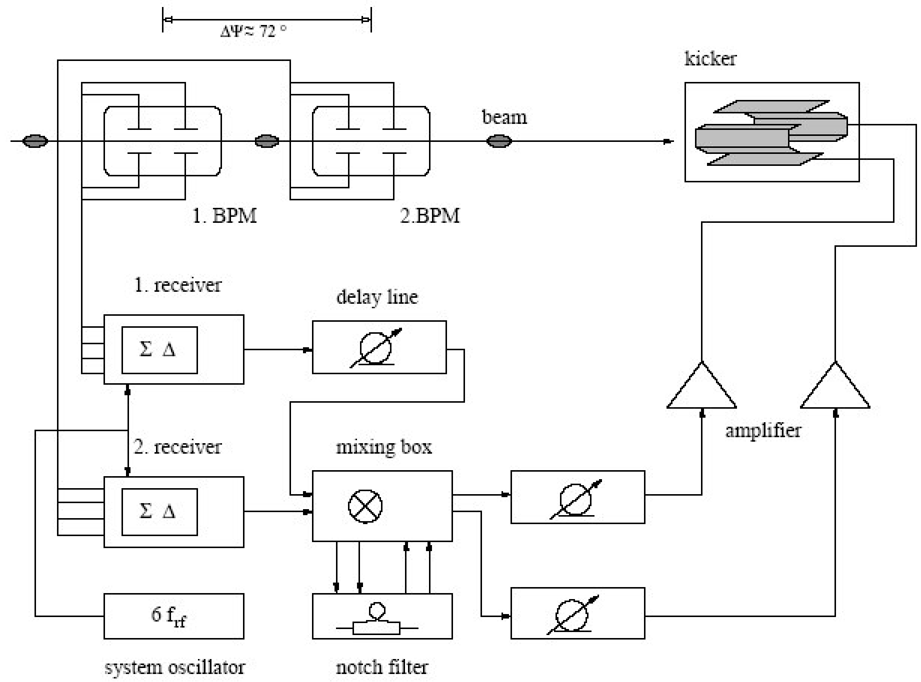
Feedback Systems

- Detect bunch offset (transverse) or bunch phase/arrival time (longitudinal)
- Do detection with high bandwidth
- Amplify signal by large factor (low noise)
- Feed back with 90 degree phase shift (kick instead of offset)



Feedback systems (practical)





- Stripline kicker (uses electrical and magnetic field) – broadband
- Signal processing electronics includes delays, mixers, amplifiers
- Notch filter to suppress DC response (and response at revolution harmonics)

Coupled bunch instability diagnostics

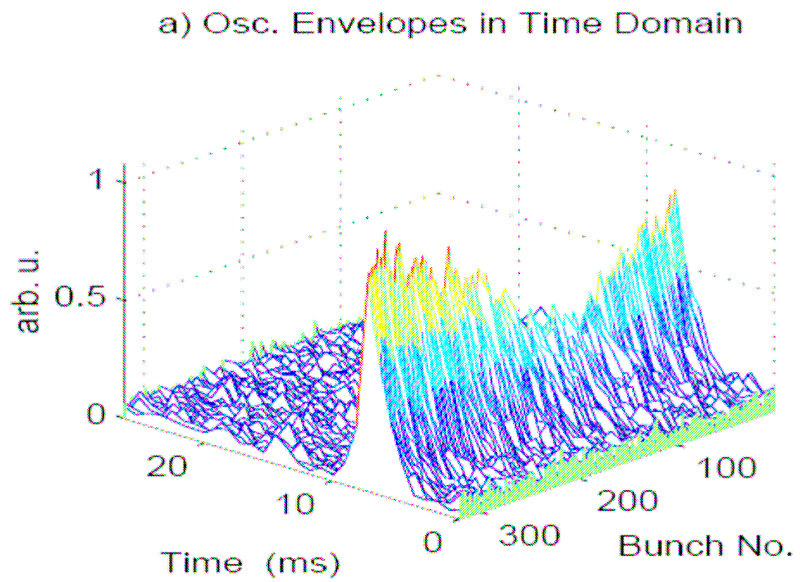


Figure 1: . Grow-Damp sequence in the horizontal plane from the ALS. The envelope of the bunch motion shows the free growth ($0 < t < 6$ms), then damping under the action of feedback ($t > 6$ms)

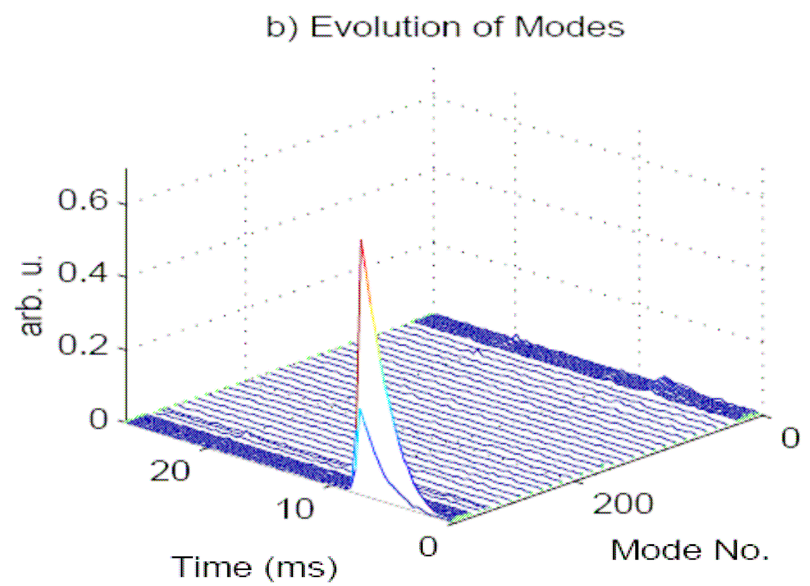


Figure 2: . The recorded bunch motion is Fourier transformed to reveal the growth of modes 326 and 327.

- Grow-damp measurements with feedback systems allow quantitative study of instabilities (and feedback performance)
  - Growth Rate
  - Damping Rate
  - Mode Pattern

More diagnostics: Cavity Temperature Scans

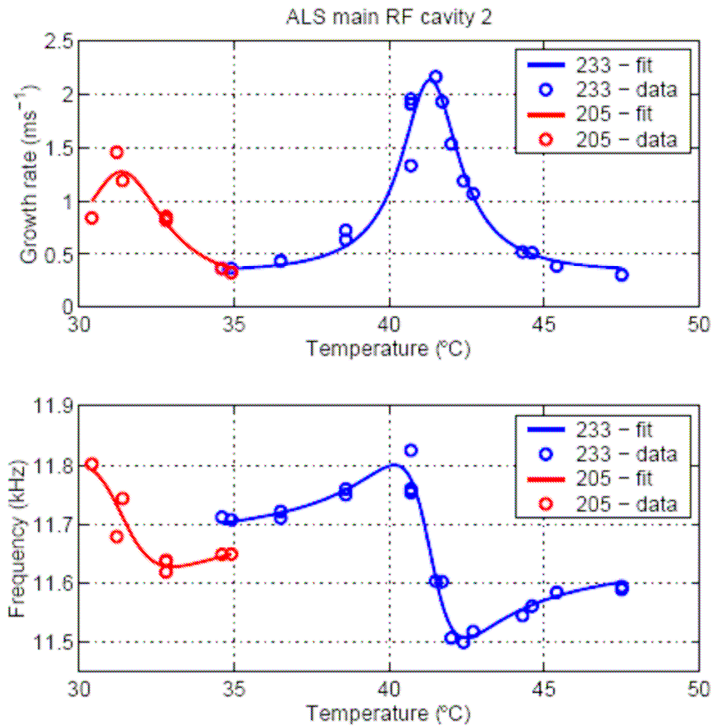
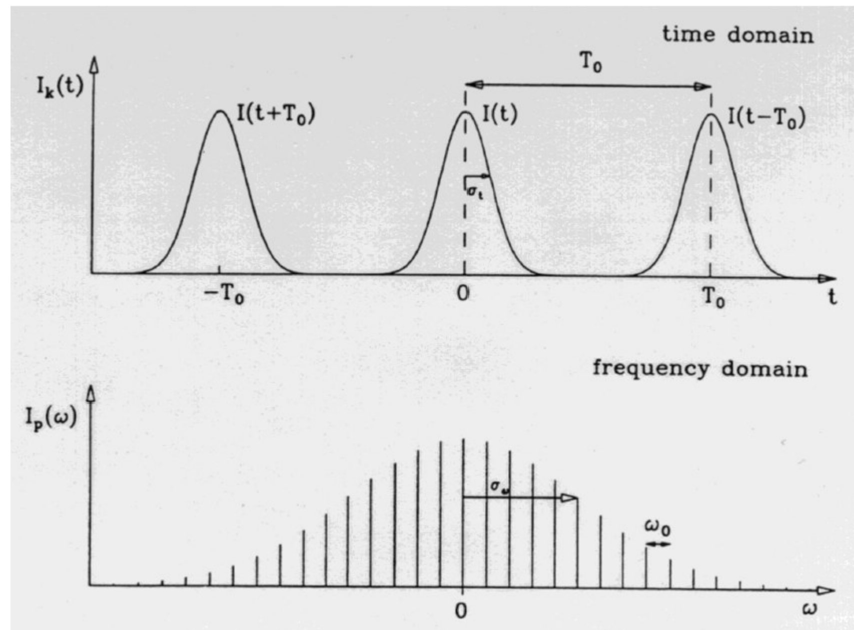


Figure 1: Growth rates (top) and oscillation frequencies (bottom) of modes 205 and 233 in main RF cavity 2 normalized to 100 mA.

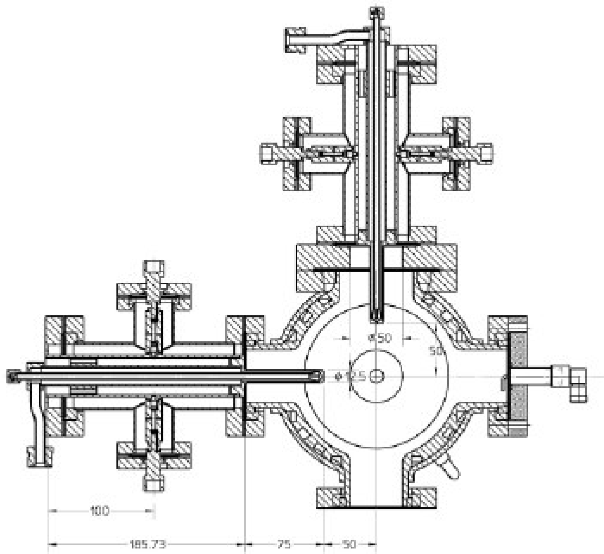


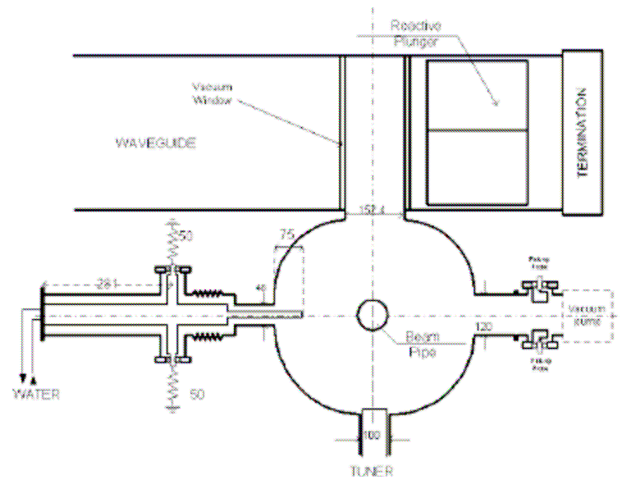
- When the temperature of a cavity is changed, the tuner/matcher loops keep the fundamental frequency constant. However, HOM frequencies will change.
- HOMs will be swept over revolution harmonics, allowing to measure their worst case effect (i.e. quantify their coupling to the beam).

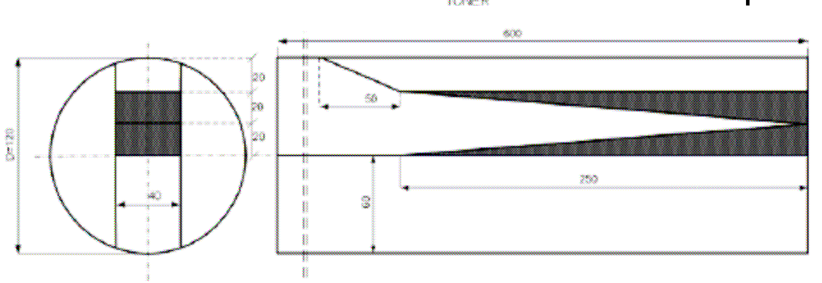
Other Diagnostics

- Diagnostics on the cavities:
  - Correlate beam measurements with signals from pickups on the cavities
  - If probes are at the right locations, one can see the excited HOMs directly.
  - Also can look at power deposited in loads of HOM dampers
- Any type of very fast (i.e. bunch-by-bunch or at least a few bunches) beamsize/beam position measurement
  - Streak camera
  - Gated CCD camera on synchrotron light port
  - Photodiodes
  - Sampling scope on BPM button signals
- Diagnostics without Beam:
  - Measure Q, R/Q of cavity HOMs on a bench before installing them
  - Calculated precise HOM spectrum with finite element code.

Countermeasures: HOM dampers







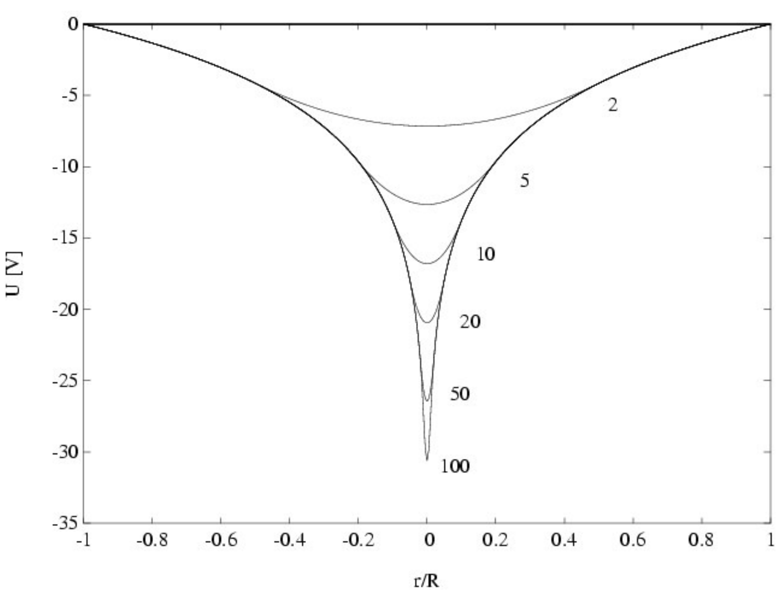
- ❖ Once one has understood, which higher order modes are the most damaging, one can design dampers to specifically target those modes.
- ❖ Newer developments (both on n/c and s/c cavities) are broadband, waveguide type dampers, which damp many modes at once.

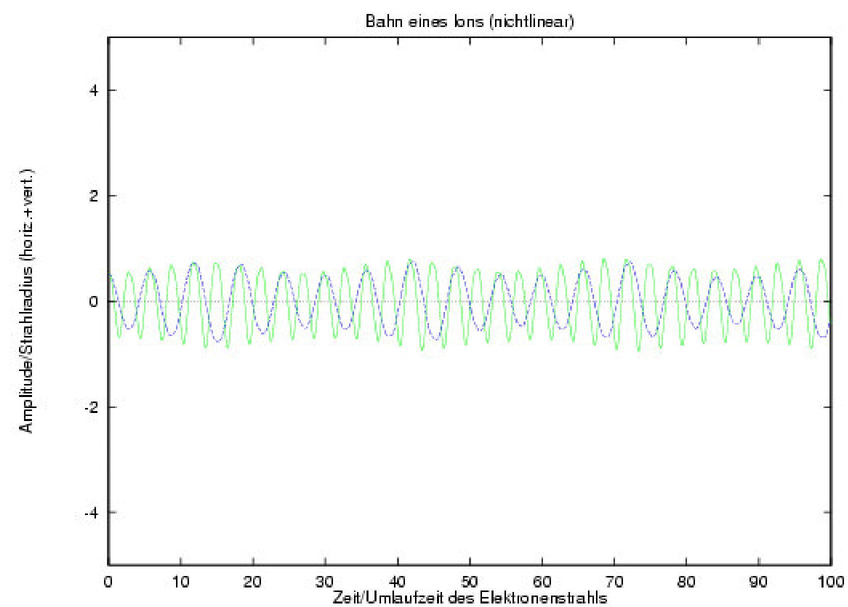
Two Stream Instabilities

- In these cases, charged ‘clouds’ (second stream) of particles is the wakefield mechanism driving the instability
- Potential mechanisms for two-stream instabilities are:
  - Ion-trapping
    - Slow ion instability
    - Fast ion instability
  - Secondary electron / Multipacting
    - Electron cloud instability

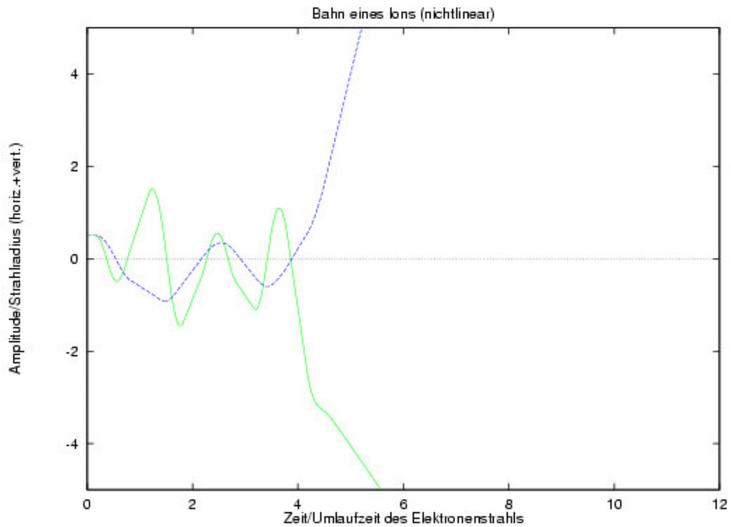
Slow Ion Trapping

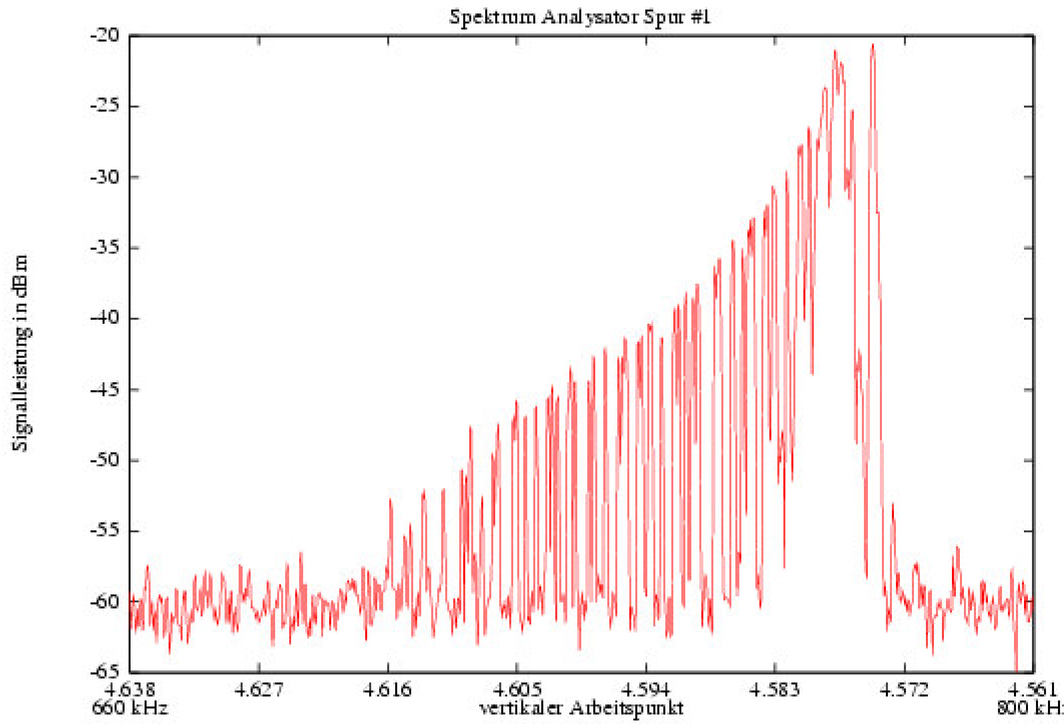
- ❖ High energy beam particles ionize residual gas
- ❖ (Mostly positive) ions can be trapped in potential of negatively charged beam
- ❖ Depending on charge and beamsize, transverse ion oscillation frequencies can be of the order of MHz and motion can be quite stable
  - Periodic focusing due to bunch passage





Slow Ion Trapping II



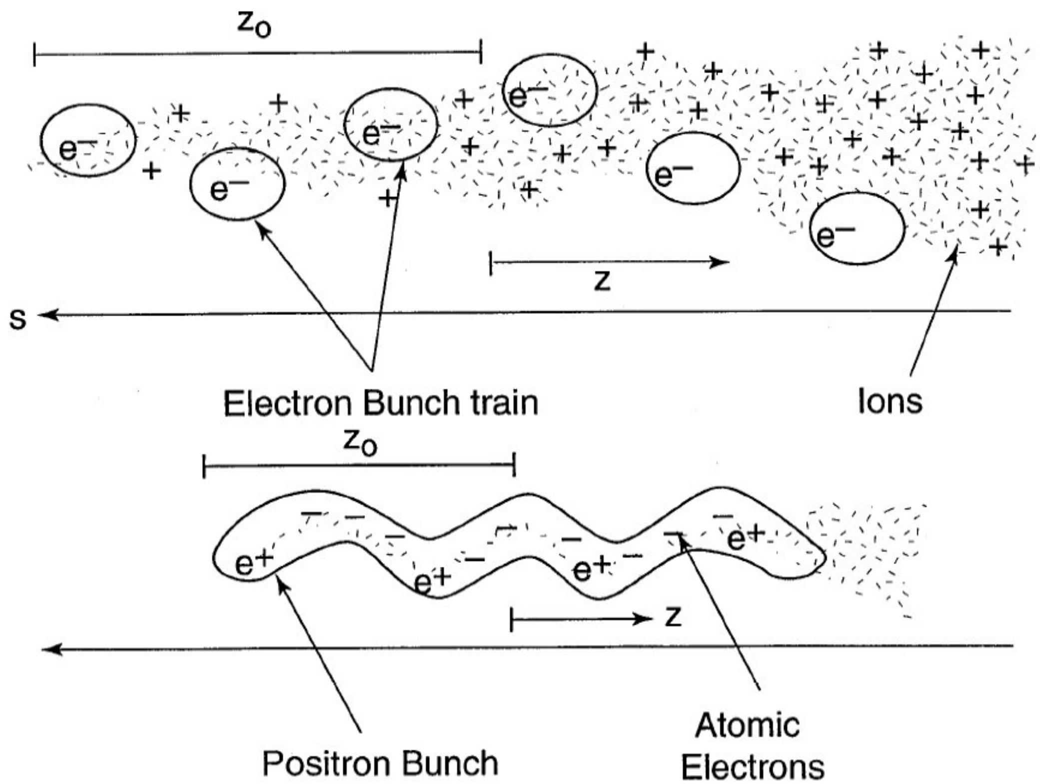


- Trapped ions can have many deleterious effects:
  - Scattering – Lifetime
  - Tune Shift
  - Instabilities (they act as an effective wakefield coupling the motion of different bunches)

Diagnostics of Ion Induced Instabilities

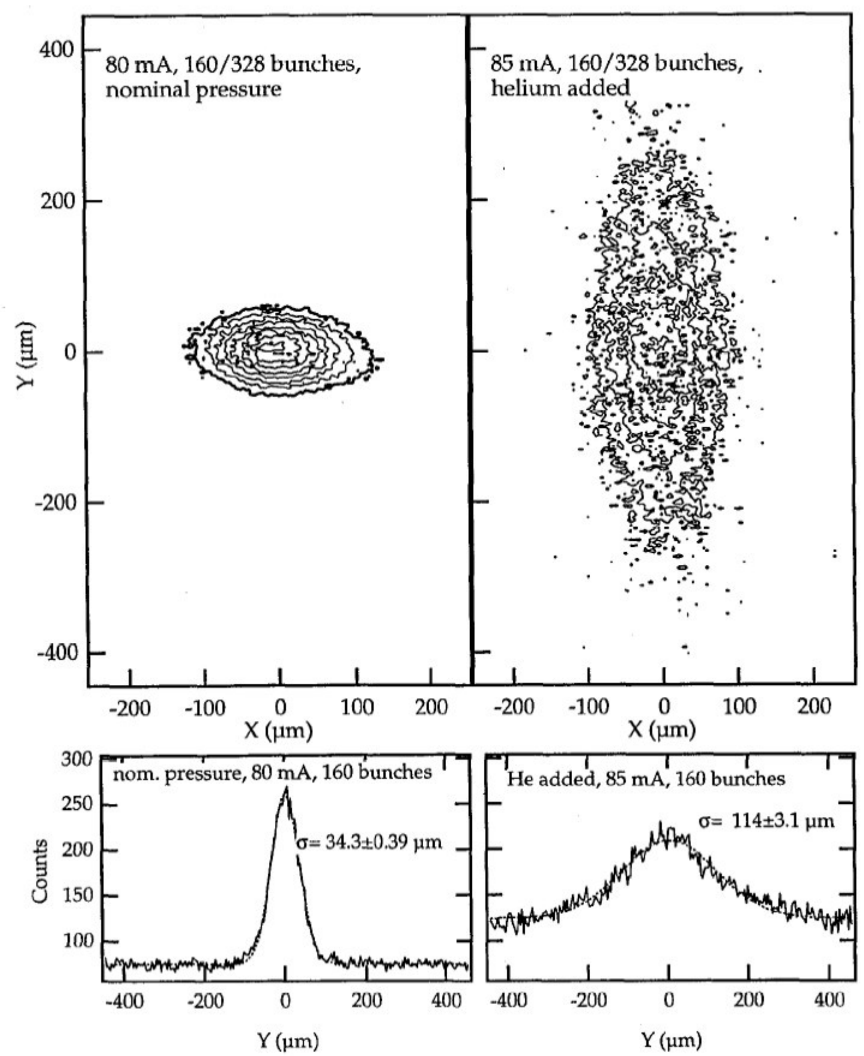
- ❖ Mode pattern of the instability:
  - Typically several neighbouring modes will become unstable at once
  - Mode frequency depends on beam current, vertical beamsize, …
- ❖ Instability disappears for long gap in the fill pattern.
- ❖ Instability depends on residual gas pressure.
- ❖ Increase in Bremsstrahlung (off the trapped ions).
- ❖ Clearing electrodes (negative bias of order of 1 kV) improve instability – current drawn by electrodes correlate with other instability observations (fill pattern …)
- ❖ Shaking of the beam might help.

Fast Ion Instability



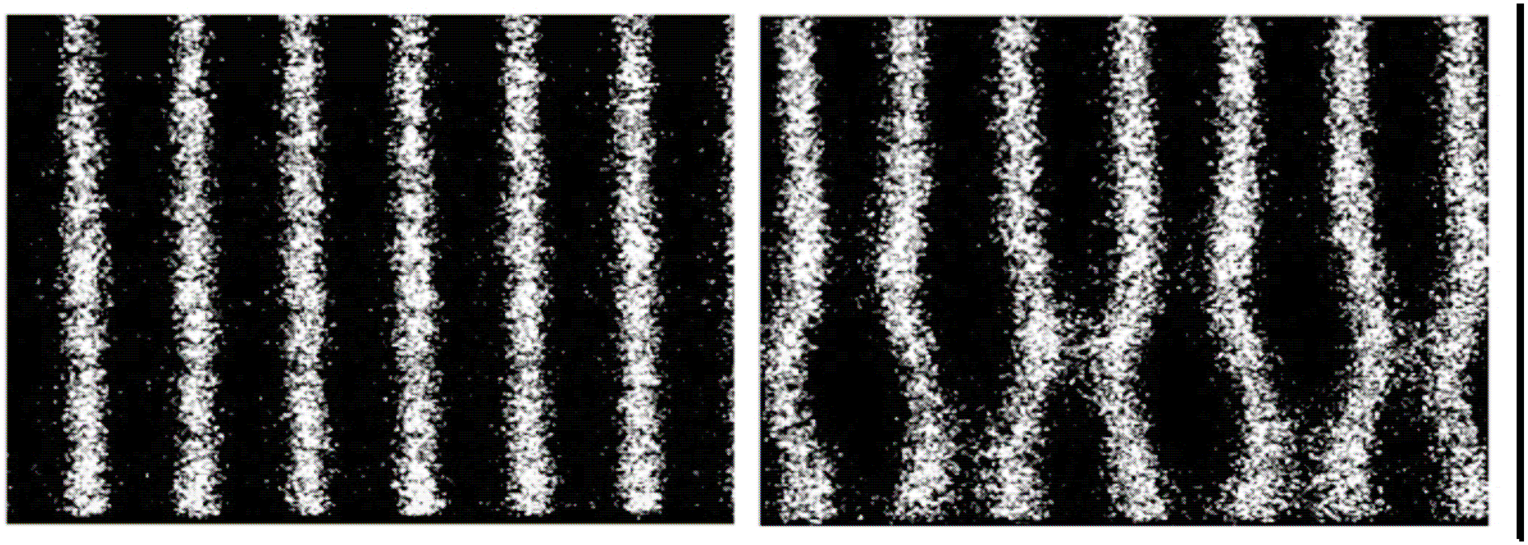
❖ If the electron current becomes very large, enough ions can be accumulated even single pass to lead to significant size increase for small emittance beams

Fast Ion Instability – Example at ALS



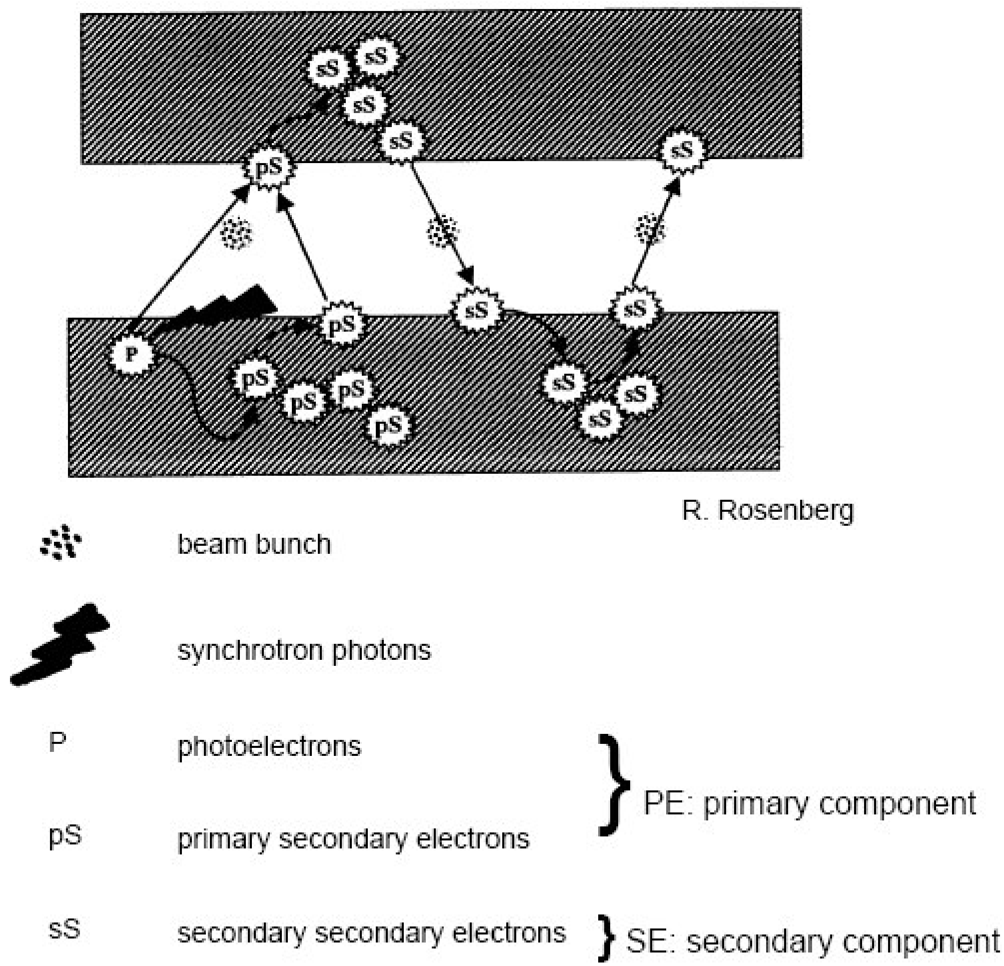
- ❖ Observe increase in projected vertical beam size
  - when He is added, single bunch beam size was increased by about 20%

Streak Camera image of fast ion instability

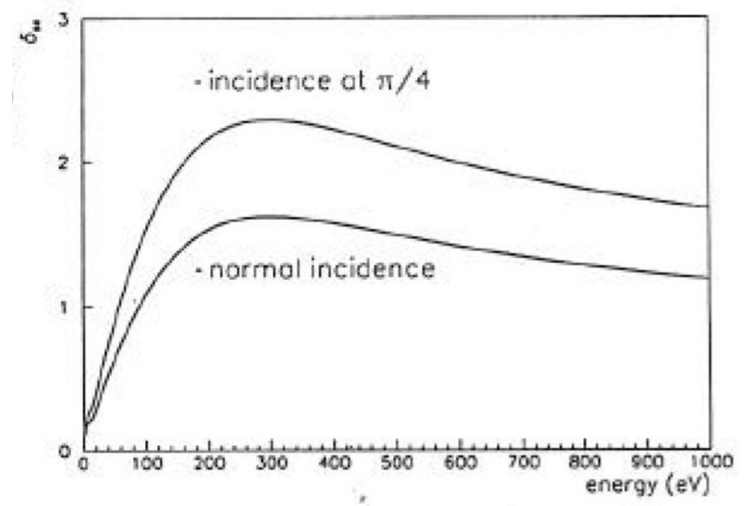


- Streak camera images of fast ion instability in PLS
- Vacuum pumps were switched off intentionally
- Clearly shows that head of bunch train stays stable whereas tail starts to oscillate
- No problem for nominal vacuum pressure
- Can be distinguished from slow ion trapping: Only tail of bunchtrain becomes unstable; increasing length of fill pattern gap does not help

Electron Cloud Instability



R. Rosenberg



- ❖ Synchrotron radiation striking vacuum chamber produces initial electrons
- ❖ Get accelerated (transversely) by bunch passage
- ❖ With SEY > 1 multiplication can occur
- ❖ (Large number of) electrons then can interact with positron/proton beam and drive instability

Practical aspects of electron cloud

- Emittance increase at high currents
- Heat load on vacuum chamber walls
- Erroneous vacuum pressure readings
  - Can be used as diagnosics
  - Can also use small electron spectrometers, analyzing the secondary electrons in the vacuum chamber.

- Countermeasures:
  - Surface treatment to reduce secondary electron yield
  - Wait for surface scrubbing to occur
  - Magnetic fields (solenoidal fields are particularly effective)
  - Gaps in bunch train